Electromagnetic characteristics of low-permittivity ceramics as substrates for mushroom-like
high impedance surfaces

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Abstract

The electromagnetic characteristics of low-permittivity ceramics, including silica, willemite, forsterite and alumina, as substrates for a mushroom-like high impedance surface (HIS) for enhancing microstrip patch antenna (MPA) performance from 1 to 6 GHz have been explored based on a parametric study evaluating the effects of ceramic substrate thickness and permittivity on resonance frequency and bandwidth of the HIS using the derived equations. To inhibit surface waves, the maximum thicknesses allowed for silica, willemite, forsterite and alumina substrates were determined for the first time when the resonance frequency of HIS matched with the operating frequency of MPA. For silica, willemite, forsterite and alumina, the thicknesses are 7.25, 5.57, 5.49 and 4.53 mm at 1 GHz, respectively, and decrease with increasing frequency in the range of 1 to 6 GHz. High impedance surfaces supported by silica, willemite, forsterite and alumina substrates exhibit bandwidths of 15.19%, 11.68%, 11.50% and 9.49%, respectively, independent of frequency. Silica, willemite and forsterite are good substrates for HISs with sufficient bandwidths. An alumina-supported HIS possesses a slightly smaller bandwidth but a more compact configuration which is favorable for antenna miniaturization. The use of low-permittivity ceramic substrates for the HIS can provide desirable electromagnetic properties while maintaining the proper dimensions to prevent surface waves.

Keywords: Electromagnetic properties; Low-permittivity ceramics; High impedance surface; Resonance frequency; Bandwidth

1. Introduction

In wireless communication, microstrip patch antennas (MPAs) are extensively used because of their low profile, low cost, lightweight and easy integration with microwave integrated circuits [1-3]. However, this type of antenna suffers a narrow bandwidth and excitation of surface waves which may significantly lower radiation efficiency. To overcome the disadvantages of MPAs, high-impedance surfaces (HISs) with sufficient bandwidths (around 10-20%) have been developed and function as a type of ground plane for MPAs to improve their performance [4]. In practice, this surface is a metallic structure characterized by presenting high electromagnetic surface impedance over a frequency band (bandgap) with two important properties: in-phase reflection and surface wave suppression. Since the surface does not reverse the phase of reflected waves, in-phase image currents are obtained. This differs from traditional metallic ground plane on which the out-of-phase image currents cancel the currents in the antenna, resulting in poor radiation efficiency. Moreover, as the surface exhibits very high impedance which suppresses both transverse electric (TE) and transverse magnetic (TM) surface waves in the bandgap, the radiation efficiency of currents on the surface and thus the antenna gain can be improved with minimization of backward radiation and reduction in mutual coupling [5,6].

A common type of HIS is mushroom-like high impedance surface because it is planar, compact and can be manufactured at low cost.⁶ The mushroom-like HIS consists of a periodic lattice of metal patches over a metallic ground plane connected by conducting vias. For structural integrity, the space between the patch and the ground plane is usually filled with a dielectric substrate. It has been found that the HIS's electromagnetic properties depend on thickness and permittivity of the substrate. The most sought-after ones are thick substrates with low

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4 permittivity (low relative dielectric constant, ϵ_r' , normally in the range of 2.2-12 [2], and small
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6 relative microwave loss factor, $\epsilon_r'' \rightarrow 0$), which provide high efficiency, wide bandwidth and
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8 loosely bound fields for radiation in the space. From this perspective, a variety of ceramic
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10 materials can be used as the HIS substrate. Some promising candidates include silica (SiO_2),
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12 silicates like willemite (Zn_2SiO_4) and forsterite (Mg_2SiO_4), and corundum group compounds
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14 such as alumina (Al_2O_3) [7-9]. However, to date, no attempt has been made to characterize these
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16 low-permittivity ceramics as substrates for a mushroom-like HIS for prevention of surface wave
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18 loss.
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24 The purpose of the present work is to investigate the electromagnetic characteristics of
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26 low-permittivity dielectric ceramics, including silica, willemite, forsterite and alumina, as
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28 substrates for a mushroom-like HIS based on a parametric study evaluating the impact of
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30 ceramic thickness and permittivity on the HIS resonance frequency and bandwidth with
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32 consideration of surface wave suppression. The findings of this work are expected to offer a
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34 useful guide for designing HISs using low-permittivity ceramic substrates for antenna
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36 applications.
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43 **2. Theory of mushroom-like HIS**

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45 Fig. 1 shows a schematic of a mushroom-like HIS in which 2-D periodic array of metal
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47 patches is etched on the surface of a dielectric substrate backed by a metal ground plane. All
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49 elements are connected to the metal ground plane with metallic conducting vias. In principle, the
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51 electromagnetic characteristics of the HIS, such as resonance frequency and bandwidth, can be
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53 tailored by modifying a variety of parameters of the structure, which include patch width W , gap
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55 width g , substrate thickness h , and substrate relative permittivity ϵ_r .
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When the HIS lattice dimensions are small compared with the operating wavelength of incident waves, the surface can be modelled as a parallel resonant inductor-capacitor (LC) circuit. The HIS presents a high surface impedance over the bandgap. The impedance (Z_s) can be determined using the following equation [6]:

$$Z_s = \frac{j\omega L}{1 - \omega^2 LC}, \quad (1)$$

where j is the imaginary unit ($j^2 = -1$), ω is the angular frequency, and L and C are, respectively, the equivalent inductance and capacitance of the surface. The inductance occurs as a result of the current flowing between the patches through the metallic vias and the capacitance arises from the proximity of adjacent patches. The values of L and C are given by [4,10]

$$L = \mu_0 \mu_r h, \quad (2)$$

$$C = \frac{W \varepsilon_0 (1 + \varepsilon_r)}{\pi} \cosh^{-1} \left(\frac{2W + g}{g} \right), \quad (3)$$

where μ_0 and ε_0 are the permeability and permittivity of free space, respectively, and μ_r is the relative permeability of the structure ($\mu_r = 1$ in this study). The resonance frequency (f_r) of the HIS can be found when the surface impedance approaches infinity. It is expressed as [11]

$$f_r = \frac{1}{2\pi\sqrt{LC}}. \quad (4)$$

The HIS supports propagation of TM surface waves at low frequencies because of its inductive surface impedance. Conversely, at high frequencies, the surface only allows propagation of TE waves because surface impedance becomes capacitive [12]. Both TE and TM surface waves are suppressed over the bandgap of the surface centered at the resonance frequency. The bandwidth (BW) corresponds to the bandgap (BG) over which the reflected wave is in-phase with the incident wave, satisfying phase of reflection coefficient (Φ) between $+90^\circ$

and -90° in engineering application ($|\Phi| \leq 90^\circ$) [13]. For the HIS constituted by nonmagnetic dielectric substrates, the BW and Φ can then be derived and given by

$$BW = \frac{BG}{f_c} \times 100\% = \frac{f_u - f_l}{f_c} \times 100\% = \frac{1}{\eta_0} \sqrt{\frac{L}{C}} \times 100\% = \sqrt{\frac{\pi h}{W(1 + \epsilon_r') \cosh^{-1}(2w/g + 1)}} \times 100\%, \quad (5)$$

$$\Phi = \text{Im} \left[\ln \left(\frac{Z_s - \eta_0}{Z_s + \eta_0} \right) \right], \quad (6)$$

where f_u is the upper frequency at which the phase of reflection coefficient equals -90° , f_l is the lower frequency at which the phase of reflection coefficient equals $+90^\circ$, f_c is the center frequency where the phase of reflection coefficient equals to 0, *Im represents the imaginary part of the expression in the square brackets*, and η_0 denotes the impedance of free space (377Ω).

As seen from Eqs. (1)-(6), thickness and permittivity of the substrate influence both resonance frequency and bandwidth of the mushroom-like HIS. Therefore, the substrate used will play an important role in determining the electromagnetic properties of the HIS.

3. Characteristics of ceramic substrates for mushroom-like HIS

To characterize the electromagnetic properties of HIS supported by silica, forsterite, willemite and alumina substrates, a preliminary parametric study showing effects of permittivity and thickness on the HIS resonance frequency and bandwidth should be carried out. Consider a mushroom-like HIS structure having a widely used metallic patch width of 10 mm and a gap width of 2 mm. *Its resonance frequency and bandwidth could be calculated using Mathematica 9.0 (Wolfram Research, Inc., Champaign, IL)*. Fig. 2 shows the resonance frequency for varying substrate thickness (0.5-10 mm) and relative dielectric constant (2.2-12). It is observed that the resonance frequency monotonically decreases with increasing relative dielectric constant and

thickness over the ranges. The lowest resonance frequency, 1.33 GHz, is obtained when the HIS has a thickness of 10 mm and a relative dielectric constant of 12. The highest resonance frequency, 12.03 GHz which is absent in Fig. 2, can be obtained when the HIS have a thickness of 0.5 mm and relative dielectric constant of 2.2. Obviously, the HIS resonance frequency can be tailored in a broad range with appropriate substrate thickness and permittivity.

Fig. 3 shows the variation of the HIS bandwidth with substrate thickness and relative dielectric constant. It is evident that the *BW* decreases with increasing relative dielectric constant. However, an opposite trend can be observed in the variation of *BW* with increasing thickness. When the substrate has a thickness of 0.5 mm and relative dielectric constant of 12, the smallest bandwidth of 6.25% is obtained. On the contrary, the largest *BW* approaches 56.38% when the HIS is constructed with a substrate having thickness of 10 mm and relative dielectric constant of 2.2.

It can be inferred from above results that the thickness of ceramic substrate is important for HIS resonance frequency and bandwidth when the substrate has a constant permittivity. Since ceramic substrate thickness determines the inductance [Eq. (2)], increasing the thickness leads to a reduction in resonance frequency and an increase in bandwidth. However, a thick substrate excites severe surface waves. An excessive large thickness also goes against the requirement of low-profile antennas and increases manufacturing costs. Thus, a compromise must be made between the performance of the HIS and design constraints of MPA. Because the HIS functions as a ground plane for MPA, the requirement for the substrate thickness of the antenna for the prevention of surface waves should also be applied to the design of the HIS even the HIS itself is capable of suppressing surface waves for the antenna. Put otherwise, to block pronounced

surface waves, the HIS substrate thickness should satisfy the following condition when the operating frequency of the antenna lies within the HIS resonance band (bandgap) [14]:

$$\frac{h}{\lambda_0} \leq \frac{0.3}{2\pi\sqrt{\epsilon_r}} \quad (7)$$

where λ_0 is the operating wavelength. When the operating frequency of the antenna matches with the HIS resonance frequency, the maximum thicknesses allowed for a HIS substrate in a given operating frequency range (e.g., commonly used low frequencies 1-6 GHz) can be derived and expressed as

$$h_{\max} = \frac{0.048\lambda_0}{\sqrt{\epsilon_r}} \quad (8)$$

Fig. 4 shows the varying $h_{\max}$ when the substrate has a relative dielectric constant ranging from 2.2 to 12 at various frequencies. The $h_{\max}$ decreases rapidly when the relative dielectric constant is less than 4 over the frequency range. However, it varies indistinctly with increasing relative dielectric constant at high frequencies. This implies that the thickness can be flexibly modified for low-dielectric constant substrates when the antenna is operated at a low frequency. On the other hand, the maximum thickness identified becomes especially important for relatively high dielectric constant materials since the HIS supported by these materials usually exhibits a relatively small bandwidth.

Fig. 5 compares the maximum substrate thicknesses allowed for the four ceramic substrates at various frequencies. The known values of dielectric constant of silica, willemite, forsterite and alumina are 3.9, 6.6, 6.8 and 10, respectively [7-9,15]. When the HIS resonates at 1, 2, 3, 4, 5 and 6 GHz at which the MPA operates, a maximum thickness of the HIS substrate with large bandwidth can be determined using Eq. (8) with simultaneous suppression of surface waves. As expected, the maximum thickness allowed decreases with increasing frequency. The

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4 respective maximum thicknesses of silica, willemite, forsterite and alumina at 1 GHz are 7.25,
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6 5.57, 5.49 and 4.53 mm. When the frequency increases to 6 GHz, the maximum thicknesses of
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8 silica, willemite, forsterite and alumina decrease to 1.21, 0.93, 0.91 and 0.75 mm, respectively. It
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10 is noteworthy that the declining trend is particularly apparent over the frequency range less than
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12 3 GHz for these particular ceramics. Thus, the ceramic substrate thickness should be reduced and
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14 strictly controlled when the MPA is aimed to operate at high frequencies. **These findings are**
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16 **important as previous investigations into improving HIS and MPA performance primarily**
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18 **focused on modifying relative permittivity and resonant frequency rather than the size of low-**
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20 **loss ceramic substrates [8,9].**
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26 Once the maximum substrate thickness is established, the corresponding metallic patch
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28 width of the HIS with a specified gap width can be determined by Eqs. (2)-(4). Fig. 6 shows the
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30 variation of patch width of ceramic-supported HIS with frequency when the gap width is fixed at
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32 2 mm. It is seen that patch width varies from 44.62 to 8.22 mm, depending on the frequency and
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34 type of ceramic substrate used. The silica-supported HIS has the largest patch width for a fixed
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36 frequency due to the lowest dielectric constant, followed by willemite, forsterite and alumina.
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38 Note that the gap width may be changed, which does not affect other electromagnetic
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40 characteristics (e.g., bandwidth) of the HIS having the same resonance frequency.
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46 Fig. 7 shows reflection phase diagrams of HISs supported by the ceramic substrates, from
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48 which the bandgaps of different ceramic-supported HIS structures, over which the Φ falls
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50 between 90° and -90° , can be identified. For all reflection phase curves, the Φ begins at 180° at
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52 low frequencies and then crosses through zero at the HIS resonance frequency ($f_r = f_c$ in this case)
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54 and continues toward -180° at high frequencies. It is inferred that the bandgap ($BG = f_u - f_l$)
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56 increases with frequency and the silica-supported HIS has the largest bandgap at the same
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frequency. The bandwidths can then be derived from the bandgaps obtained in Fig. 7 according to Eq. (5). Fig. 8 shows a plot of bandwidth versus frequency. Unlike the variation of bandgap with frequency, the ceramic-supported surfaces present nearly unchanged bandwidths in the frequency range of 1-6 GHz. The bandwidths of HIS supported by silica, willemite, forsterite and alumina substrates are found to be 15.19%, 11.68%, 11.50% and 9.49%, respectively. It is revealed that besides alumina, silica, willemite and forsterite-supported high impedance surfaces possess sufficient bandwidths ($>10\%$). The alumina-supported HIS structure exhibits a slightly lower bandwidth due to its relatively high dielectric constant. Nevertheless, it has a more compact (smaller h and W) configuration, which is favorable for antenna miniaturization [16].

From the above results, it can be concluded that the low-permittivity ceramics including silica, willemite and forsterite are good substrates for HISs with desirable electromagnetic properties for MPA applications when these substrates are designed with the maximum thicknesses allowed to inhibit surface waves. Compared with silica, willemite and forsterite substrates, the alumina substrate has a relatively higher relative dielectric constant resulting in miniaturization but an insufficient bandwidth for the HIS. Overall, a compromise has to be made between performance and miniaturization in the design of HISs for antenna applications.

4. Conclusions

The electromagnetic properties of low-permittivity ceramics as substrates for the mushroom-like HIS for improving MPA performance have been investigated with consideration of suppressing surface waves. The analysis is based on a parametric study evaluating the effects of ceramic substrate thickness and permittivity on the HIS resonance frequency and bandwidth using the derived equations. Four common low-permittivity dielectric ceramics, including silica,

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4 willemite, forsterite and alumina, were examined in the frequency range from 1 to 6 GHz. To
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6 block surface wave propagation, the maximum thicknesses allowed for these ceramic substrates
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8 were determined when the HIS resonance frequency matched with the operating frequency of
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10 MPA. The maximum thicknesses allowed for silica, willemite, forsterite and alumina substrates
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12 at 1 GHz are, respectively, 7.25, 5.57, 5.49 and 4.53 mm, and the thicknesses decrease
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16 supported by silica, willemite, forsterite and alumina substrates exhibit bandwidths of 15.19%,
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18 11.68%, 11.50% and 9.49%, respectively, independent of frequency. Silica, willemite and
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20 forsterite are good substrates for HISs with sufficient bandwidths for MPA applications. For an
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22 alumina-supported HIS, it possesses a slightly smaller bandwidth but a more compact
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24 configuration than its counterparts and, therefore, is favorable for antenna miniaturization. It is
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26 evident that these low-permittivity dielectric ceramics are promising substrate candidates for
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28 implementing a HIS with desired electromagnetic properties while maintaining the proper
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30 dimensions for blocking propagation of surface waves. These findings are expected to be useful
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32 for the HIS design that incorporates ceramic substrates for low-profile antenna applications.
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Figure captions:

Fig. 1. Schematic of a mushroom-like high impedance surface.

Fig. 2. Variation of resonant frequency with substrate thickness and relative dielectric constant.

Fig. 3. Variation of bandwidth with substrate thickness and relative dielectric constant.

Fig. 4. Variation of maximum substrate thickness with relative dielectric constant at different frequencies: *a*-1GHz, *b*-2 GHz, *c*-3GHz, *d*-4GHz, *e*-5GHz and *f*-6 GHz.

Fig. 5. Variation of maximum substrate thickness with frequency for high impedance surfaces supported by different ceramic substrates.

Fig. 6. Variation of patch width with frequency for high impedance surfaces supported by different ceramic substrates.

Fig. 7. Reflection phase diagrams of high impedance surfaces supported by different ceramic substrates.

Fig. 8. Variation of bandwidth with frequency for high impedance surfaces supported by different ceramic substrates.

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