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

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

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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 permittivity (low relative dielectric constant, $\varepsilon_r^{'}$, normally in the range of 2.2–12 [2], and small relative microwave loss factor, $\varepsilon_r^{''} \to 0$), which provide high efficiency, wide bandwidth and loosely bound fields for radiation in the space. From this perspective, a variety of ceramic materials can be used as the HIS substrate. Some promising candidates include silica (SiO_2), silicates like willemite (Zn_2SiO_4) and forsterite (Mg_2SiO_4), and corundum group compounds such as alumina (Al_2O_3) [7–9]. However, to date, no attempt has been made to characterize these low-permittivity ceramics as substrates for a mushroom-like HIS for prevention of surface wave loss.

The purpose of the present study is to investigate the electromagnetic characteristics of low-permittivity dielectric ceramics, including silica, willemite, forsterite and alumina, as substrates for a mushroom-like HIS based on a parametric study evaluating the impact of ceramic thickness and permittivity on the HIS resonance frequency and bandwidth with consideration of surface wave suppression. The findings of this study are expected to offer a useful guide for designing HISs using low-permittivity ceramic substrates for antenna applications.

2. Theory of mushroom-like HIS

Fig. 1 shows a schematic of a mushroom-like HIS in which a 2-D periodic array of metal patches is etched on the surface of a dielectric substrate backed by a metal ground plane. All elements are connected to the metal ground plane with metallic conducting vias. In principle, the electromagnetic characteristics of the HIS, such as resonance frequency and bandwidth, can be tailored by modifying a variety of parameters of the structure, which include patch width W, gap width g, substrate thickness h, and substrate relative permittivity ε_r.

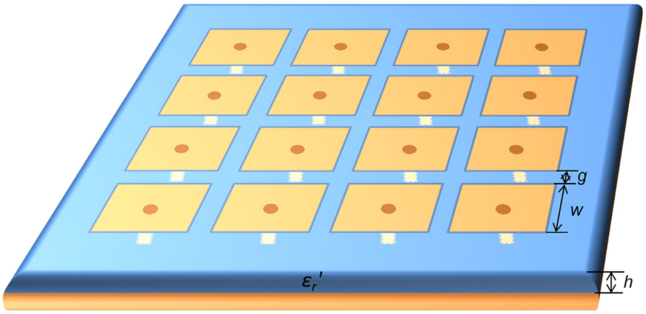

Fig. 1. Schematic of a mushroom-like high impedance surface.

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]:

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

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]

$$L = \mu_0 \mu_r h, \tag{2}$$

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

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 (μ_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]

$$f_r = \frac{1}{2\pi\sqrt{LC}}. \tag{4}$$

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

$$\begin{aligned} BW &= \frac{BG}{f_c}\times 100\% = \frac{f_u - f_l}{f_c}\times 100\% = \frac{1}{\eta_0}\sqrt{\frac{L}{C}}\times 100\% \\ &= \sqrt{\frac{\pi h}{W\left(1+\varepsilon_r^{'}\right)\cosh^{-1}\left(2w/g+1\right)}}\times 100\%, \end{aligned} \tag{5}$$

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

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 0, Im represents the imaginary part of the expression in the square brackets, and η_0 denotes the impedance of free space (377 Ω).

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