Effective surface impedance of anisotropic surface roughness

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Surface roughness usually has a detrimental effect on the performance of antennas and other RF devices. This effect is particularly important for 3D printed devices, and it must be accounted for when the devices are simulated. Furthermore, the surface roughness of 3D printed devices is usually anisotropic, due to the raster scanning inherent to most 3D printing processes. The two most commonly used models to account for the surface roughness, those of Hammerstad and Jensen, or Lukić and Filipovic, are based on empirical fits of simulated data, and do not account for anisotropy. A recent model by Gold and Helmreich (IEEE Trans. Microw. Theory Tech., 65, 3720–3732, 2017) is based on physical mixture laws, but does not account for anisotropy either.

To account for surface roughness in a systematic way including the effect of anisotropy, we propose to divide the surface in a series of sublayers. In each sublayer, the effective permittivity, ϵ_{eff}, is calculated using the Bruggeman effective medium approximation,

$$\frac{\epsilon_{\mathrm{eff},j}-\epsilon_0}{\epsilon_0+L_j(\epsilon_{\mathrm{eff},j}-\epsilon_0)} = f_{\mathrm{m}}\frac{\epsilon_{\mathrm{m}}-\epsilon_0}{\epsilon_0+L_j(\epsilon_{\mathrm{m}}-\epsilon_0)}, \tag{1}$$

where ϵ_{m}, and ϵ_0 are the permittivity of the metal and vacuum, respectively; f_{m} is the fraction of metal in the sublayer; and L is the depolarization factor depending on the shape of the roughness. The subscript j indicates the two in plane axis x and y or the out of plane axis z. The depolarization factor, which determines the anisotropy, is

$$L_{x,y} = \frac{U_x U_y}{2}\int_0^{\infty}\frac{\mathrm{d}s}{(s+U_{x,y}^2)\sqrt{(s+U_x^2)(s+U_y^2)}}, \quad L_z = 0, \tag{2}$$

where U_j are the typical dimensions of the roughness in the in-plane axes, and s is an integration variable.

With this approach, the surface roughness can be replaced in a full wave simulation by a few anisotropic layers. However, even this approach might be impractical since those thin layers require a dense mesh that slows down the calculations.

When the surface roughness is thin relative to the wavelength of the wave (which is the technologically relevant case), the simulation of the surface roughness can be further simplified by representing it by an anisotropic effective surface impedance. This surface impedance can be determined by calculating the ratio of the electric and magnetic fields at the surface for two different field polarizations, which can be obtained from simple one dimensional simulations.