3C2-2

Enhance Efficiency of High Frequency Antennas using Lossy Metamaterials

#Florent Jangal [1], Nicolas Bourey [1]
[1] Onera – The French Aerospace Lab
F-91761 Palaiseau, Florent.Jangal@onera.fr

1. Introduction

It is well-known that low frequency waves are propagated beyond the Line-of-Sight (LoS) [1]. In the High Frequency (HF) band (i.e. between 3 MHz and 30 MHz), this property is turned to good account, by radar and communication systems, in order to cover very large areas. Two propagation modes have to be distinguished: the surface wave mode and the sky wave mode. In the first one, the wave is guided by the air / ground interface. As a consequence, the surface waves follow the earth curvature and reach non-LoS regions. Sky waves, as for them, are refracted by the ionosphere at very large distance (Figure 1).

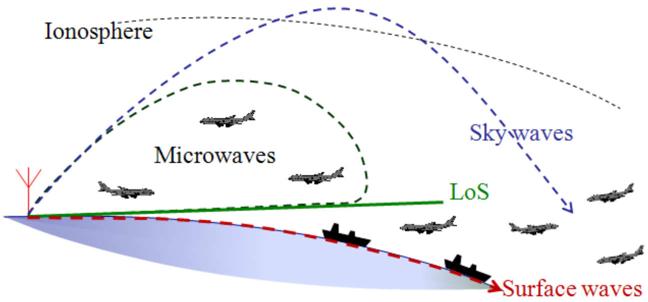

Figure 1: HF propagation modes allow covering areas beyond the LoS.

Antennas of operational radar systems, except for the CODAR [2], are monopole type or biconical type [3]. Due to the soil vicinity, those antennas are always radiating energy in the sky wave mode as well as in the surface wave mode. As a result, surface wave radars are perturbed by ionospheric clutter (i.e. effects of unwanted sky wave mode) and sky wave radars cannot reach directly very far off areas (i.e. effects of energy waste at low angles in surface wave mode) [4][5]. The issue is: how to select only the desired propagation mode?
There is an extensive work on metamaterials, surface waves and leaky waves. Nevertheless, those studies cannot be transposed in a straight line in the HF band. Indeed, the losses in the soil cannot be neglected and the size of metallic elements should be kept reasonable to avoid overspend of radiating elements.
In this paper, we are showing how, specific periodic sub-lambda structures can overcome the issue. In section 2, we highlight the effects of losses on metamaterials. In section 3, we detailed our solution and give some results. Section 4 is dedicated to the conclusion.

2. Losses in metamaterials

Figure 2 depicts the layout of the widely known mushroom-like metamaterial proposed by Sievenpiper [6]. The surface impedance z is given by:

$$z = j\frac{2\pi \cdot f \cdot L}{1-(2\pi \cdot f)^2 \cdot L \cdot C} \qquad (1)$$

$$L = \mu \cdot t \qquad (2)$$

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

Where f is the carrier frequency; L and C are the equivalent inductance and capacitance of the mushrooms; μ, ε_0 and ε_r are the vacuum permeability, the vacuum and the relative permittivity of the substrate; t, w and g are the thickness of the substrate, the width of the mushrooms and the space between two mushrooms.

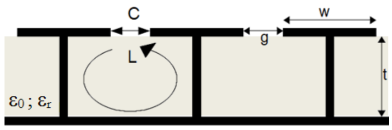

Figure 2: Mushroom layout

In our case the substrate is the lossy soil. Thus, the relative permittivity to consider is the complex one (4). Hence, the capacitor C depends on the frequency and has a real part and an imaginary part (i.e. $C = C' + jC''$). At the resonance frequency, the maximum surface impedance is bounded by (6) and no longer tends to infinity.

$$\varepsilon_r = \varepsilon_r' + j\cdot\varepsilon_r'' = \varepsilon_r' + j\cdot\frac{\sigma}{2\pi\cdot f\cdot\varepsilon_0} \quad (4)$$

$$Z = \frac{j\cdot 2\pi\cdot f\cdot L}{1 - C'\cdot L\cdot(2\pi\cdot f)^2 - j\cdot C'' L\cdot(2\pi\cdot f)^2} \quad (5)$$

$$Z_0 = \frac{1}{C''\cdot 2\pi\cdot f} \quad (6)$$

At last we should consider the resistance R of the region between mushrooms. The impedance at the resonance is then bounded by:

$$Z_{0(f)} = \frac{R(f)}{1 - C''(f)\cdot R(f)\cdot 2\pi\cdot f} \quad (7)$$

As shown in Figure 4, the losses dramatically change the behavior of the metamaterial depicted in Figure 3. Nevertheless, a strong resonance can be obtained for particular set of parameters t, g and w. Since the parametric form of (6) does not allow an analytic study, we are using CST MicroWave Studio to optimize the shape of the periodic structure.

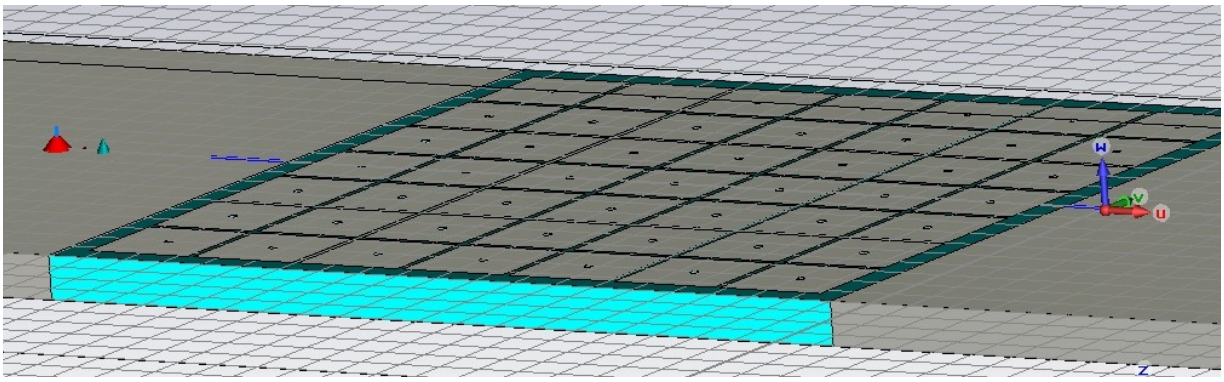
Figure 3: Simulated metamaterial structure

3. Optimization of metamaterial for sky wave mode or surface wave mode

Despite the fact that losses make metamaterial shape more difficult to set up, they allow to easily solve the issue concerning the metallic ground plane located under the substrate. As shown in Figure 5, when the thickness increases, the band-gap intensity increases, at least up to the penetration depth. Thus, the metallic ground plane is useless. This point is quite logical since skin effect intrinsically limits thickness of the substrate.

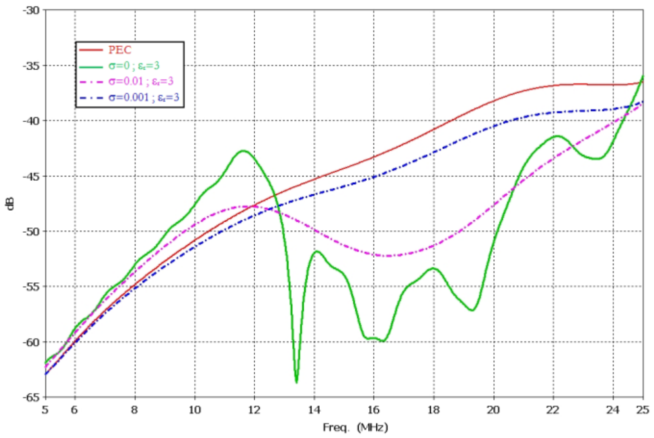

Figure 4: Comparison of transmission coefficients when the substrate is filled with PEC (red), loss-free dielectric (green) and lossy dielectric (wet soil in blue dashed-dot and dry soil in pink dashed-dot), the band-gap disappears when the losses increase.

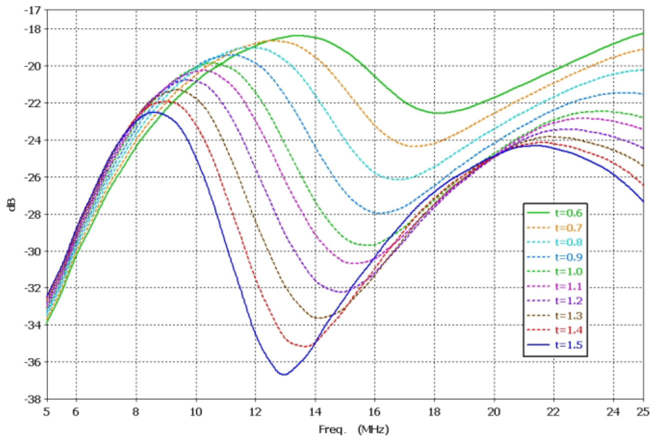

Figure 5: Evolution of the band-gap with regard to the thickness *t* (in meter) of the substrate**.**

3.1 Sky wave mode

In sky wave radar, the lower the elevation is, the larger the coverage is. Hence, surface wave propagation has to be altered in order to enhance sky wave radiation at low elevation angles [7]. Optimization of the metamaterial shape is based on the ratio of field radiated at low elevation and the field radiated at high elevation. After an optimization cycle, we obtain an improved radiation pattern. Figure 6 depicts a comparison between the proposed structure and the antenna currently in use (i.e. biconical antenna of NOSTRADAMUS radar [8]).

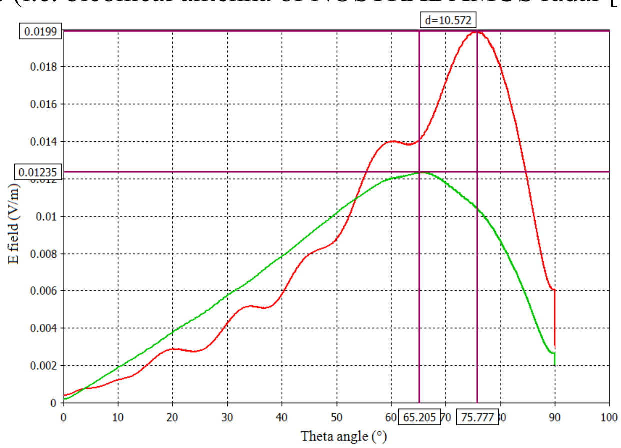

Figure 6: Comparison of field repartition between the NOSTRADAMUS antenna (green) and the proposed antenna (red), the gain is around 4 dB and the main direction is shifted of 10°.

3.2 Surface wave mode

It has been shown by Petrillo and al. [9] that, the surface impedance of the soil conditioned the energy repartition between surface waves and sky waves. According to section 2, it is possible to sweep over numerous surface impedances by modifying the material shape. As shown in Figure 7, radiation in surface wave mode can be increased (light blue) when the impedance reaches the conditions introduced in [9].

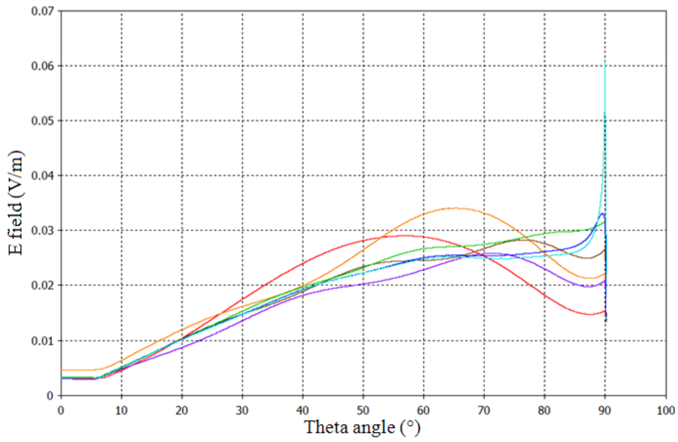

Figure 7: Evolution of field repartition according to metamaterial shape, the initial pattern (red) is firstly improved in sky wave mode (orange), then the pattern becomes flat (brown, green and violet), at last surface waves are generated (dark and light blue)

4. Conclusion

In radar and communication domains, High Frequencies allow reaching non-LoS regions. Nevertheless, there is not specific antenna for sky wave systems or surface wave systems. Sky wave systems are limited in range, due to energy waste at low elevation angle, while surface wave systems are perturbed by unwanted sky wave energy waste.

We have proposed here to use metamaterial approach to design specific antennas. We have shown that, losses, which cannot be ignored at low frequency, modify dramatically the metamaterial behavior. But, they also allow suppressing the metallic sheet generally located below the metamaterial substrate.

After an optimization of the metamaterial shape, we have shown that the band gap can be retrieved. According to metamaterial shape, the surface impedance can be fitted to enhance radiation of surface waves or low elevation sky waves. As a consequence, we are able to overcome the issue of energy waste in the unwanted HF propagation modes.

References

[1] V. Bazin *et al.*, "Tracking vessels up to the EEZ limits: complementarities of HF sky wave and HF surface wave radars", Proc. MAST Conference, Washington, 2011.

[2] D.E. Barik *et al.*, Circular Superdirective Receive Antenna Arrays, US Patent 006844849 B1, 2005.

[3] J.M Headrick, "Looking over the horizon (HF radar)", IEEE Spectrum , vol.27, no.7, pp.36-39, July 1990.

[4] F. Jangal *et al.*, "Wavelet contribution to remote sensing of the sea and target detection for a high-frequency surface wave radar", IEEE GRSL, vol.5, no.3, pp.552-556, 2008.

[5] M. Darces *et al.*, "Optimizing a HF biconical antenna for an OTH radar", Proc. USRI, Ottawa, 2007.

[6] T.T. Nguyen *et al.*, "Design of a Wideband Mushroom-like Electromagnetic Bandgap Structure with Magneto-Dielectric Substrate", Proc. Of ICITA, Hanoi, pp. 978-981, 2009.

[7] F. Jangal *et al.*, "Towards HF metamaterials", Proc. LAPC, Loughborough , pp.629-632, 2009.

[8] V. Bazin *et al.*, "A general presentation about OTH-Radar NOSTRADAMUS", Proc. Radar, Verony, pp. 634-643, 2006.

[9] L. Petrillo *et al.*, "Negative permittivity media able to propagate a surface wave", PIER, Vol. 115, pp. 1-10, 2011.