A Novel Implementation of Thin High-Impedance Surfaces

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Abstract

A novel high impedance structure is proposed using left-handed structure. The lumped elements: inductor in shunt and capacitor in series, are placed in the microstrip line in order to configure this left-handed material. For an easy adjustment of these lumped components, the phase of the reflection coefficient is simulated on the variation of these parameters after the explanation of the operating principle. It is seen in the optimized result that the phase is controlled in a very flat curve over the examined frequency range from 1GHz to 3GHz, exhibiting the characteristic of a broad-band high-impedance surface.

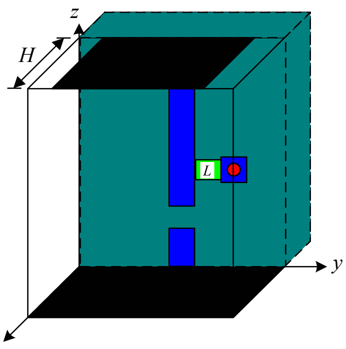
1. Introduction

After the high impedance surface (HIS) was firstly investigated in papers [1] and [2], it has aroused many applications. In [1] and [2], its geometry is similar to a corrugated metal surface and the corrugations have been folded up into lumped-circuit elements in a two-dimensional way. It exhibits high impedance in a certain frequency band over which it can restrain the propagation of surface waves. In [3], a novel compact high-impedance surface with interdigital structure was presented to increase the fringe capacitor and compress the overall size of the high-impedance surface. A new high-impedance surface for applications in antenna and microwave circuit was suggested in [4]. This structure has wider bandwidth than that of the multi-layered mushroom structure in addition to its angular and polarization stability of the resonance. A high impedance surface can be very useful in designing absorbing materials [5] and small antennas.

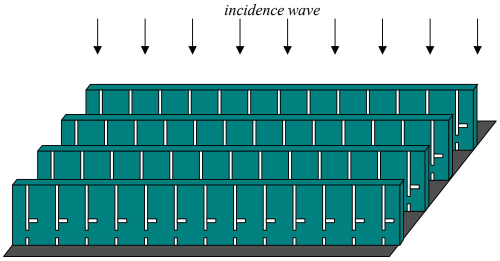
In this work, a novel high-impedance surface with one-stage or two-stage L-C structure is presented. The lumped elements have been added into the traditional transmission line so as to construct the left-handed material. The inductor in shunt and capacitor in series are used because they can be adjusted easily to exhibit the left-handed characteristic. The basic operating principle is explained in the next section with the introduction of the unit-cell structure. Based on the theoretical analysis, the simulated reflection coefficient's phase has been plotted in Section 3 according to the variation of the parameters like inductance, capacitance and microstrip line width. Lastly, the optimized results are given and they show that the phase has been controlled in a very flat range covering the desired frequency band from 1GHz to 3GHz.

2. The Operating Principle

In order to design this novel high-impedance surface using the left-handed transmission line (LH-TL), it is necessary to construct such a unit cell by means of a microstrip line with lumped elements confined by a pair of parallel-plates: one above the top and the other at the bottom of the substrate. As shown in Fig. 1 (a), many of these cells can then be assembled periodically together to construct the high-impedance surface when the incident wave is travelling downward upon the micorstip line, as illustrated in Fig. 1 (b).



(a)



(b)

Fig. 1 Geometry of the proposed LH-TL high-impedance surface (a) One-stage unit cell; (b) Periodic structure.

A. *One-stage Case*

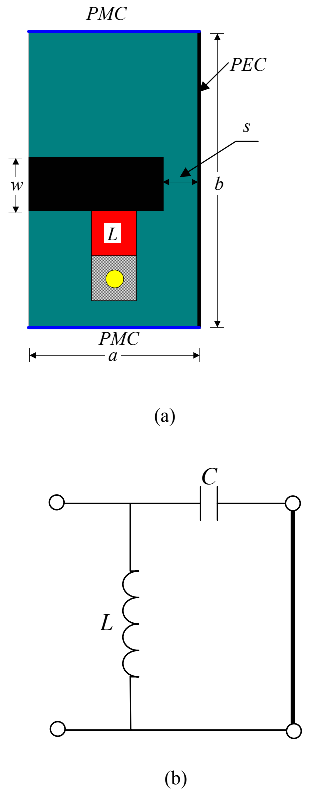


Fig. 2 One-stage LH-TL structure terminated with a short- circuit (a) Top view of the unit cell; (b) Equivalent circuit.

As the structure must be terminated with a conducting plate, each unit cell is equivalent to a capacitor *C* and an inductor *L* both in shunt ignoring the microstrip line's distribution effect. The input impedance Z_{in} and reflection coefficient Γ are expressed in the following equations (1) and (2), respectively:

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

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \quad (2)$$

where ω is the angular frequency and Z_0 is the characteristic impedance of the microstrip line. Therefore, the phase of Γ can be expressed by *L* and *C* as follows:

$$\phi_\Gamma = \pi - 2\tan^{-1}\left[\frac{\omega L}{Z_0\left(1-\omega^2 LC\right)}\right] \quad (3)$$

From equation (3), it is clear that the surface of this left-handed structure has the high-impedance characteristic if the components *L* and *C* are tuned to satisfy the resonant condition of

$$LC = 1/{\omega_0}^2 \quad (4)$$

where ω_0 is the central resonant frequency. The reflection coefficients Γ of an ideal high-impedance surface should be unity at any frequency. However, it is difficult to ensure that the phase maintains to be zero over a wide frequency range and we have to make it nearly at zero with the slope of the phase at the central frequency minimized. According to equation (3), it is derived that

$$\left|\frac{\partial \phi_\Gamma}{\partial \omega}\right|_{\omega=\omega_0} = 4CZ_0 \quad (5)$$

From the result in equation (5), it can be found that the value of *C* should be adjusted as small as possible to lower the slope.

B. *Two-stage Case*

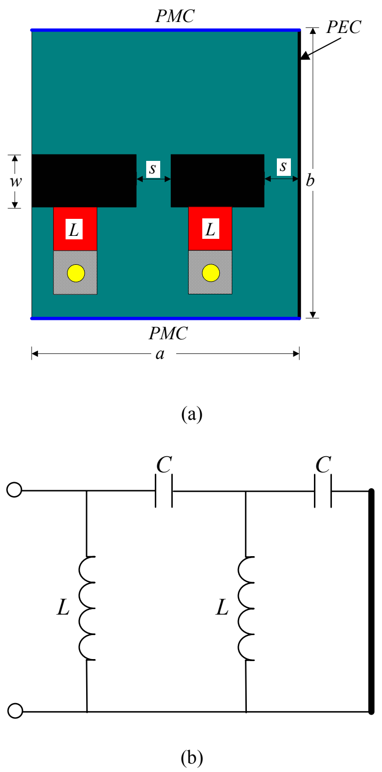


Fig. 3 Two-stage LH-TL structure terminated with a short- circuit (a) Top view of the unit cell; (b) Equivalent circuit.

Further work is carried out for the two-stage case shown in Fig. 3 (a) for possible improvement in the left-handed performance. In this case, the respective capacitor and inductor are assumed to be the same as C and L in the equivalent circuit in Fig. 3 (b) for a simplified analysis. The phase of the reflection coefficient is formulated in equation (6). Different from the one-stage case, there are two resonant frequencies ω_1 and ω_2 and the frequency-dependent slope of the phase is illustrated in equations (7) and (8).

$$\phi_\Gamma = \pi - 2\tan^{-1}\frac{\omega L}{Z_0\left[1-\omega^2 LC\dfrac{1-\omega^2 LC}{2-\omega^2 LC}\right]} \qquad (6)$$

$$\text{For } \omega_1 = \frac{0.618}{\sqrt{LC}},\ \left|\frac{\partial\phi_\Gamma}{\partial\omega}\right|_{\omega=\omega_1} = 38CZ_0 \qquad (7)$$

$$\text{For } \omega_2 = \frac{1.618}{\sqrt{LC}},\ \left|\frac{\partial\phi_\Gamma}{\partial\omega}\right|_{\omega=\omega_2} = 2.112CZ_0 \qquad (8)$$

It is also seen in these equations that the small value of C leads to a lower slope of the phase. Due to the large slope in the first resonant frequency, it needs to be adjusted out of the desired frequency range.

3. Parametric Study

Based on the previous analysis of the high-impedance characteristic of the proposed structure, the parameters of the one-stage structure should be further varied to examine their effects on the reflection coefficient. In the top view of Fig. 3 (a), the small capacitor is substituted by the gaps between the microstrip line and the backed conducting plate, whose capacitance is about several tens of pico-Farads.

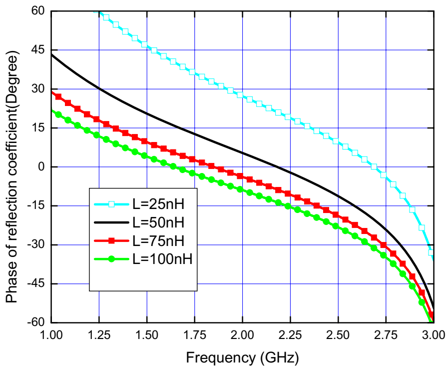


Fig. 4 The influence of the inductance L on the reflection coefficient's phase (a=5mm, b=40mm, H=18mm, w=1mm, s=3.5mm).

Fig. 4 shows the frequency response of the reflection coefficient's phase under the variation of the shunt inductor L. When the inductance increases, the corresponding curve is shifted left to lower level. The resonant frequency at which the phase is zero is decreased with the increment of inductance. This also can be verified by equation (3).

It is seen from equations (5), (7) and (8) that smaller capacitance results in a flat curve of the phase. In the structure, the small capacitance is produced by the capacitive gap illustrated in Fig. 2 (a). The result in Fig. 5 demonstrates the relation between the gap s and the reflection coefficient's phase. As the increment of s leads to the decrement of the capacitance, the resonant frequency is also shifting right as expected. Meanwhile, it is noticed that the curve is getting flatter near the resonant frequency with the increment of the gap.

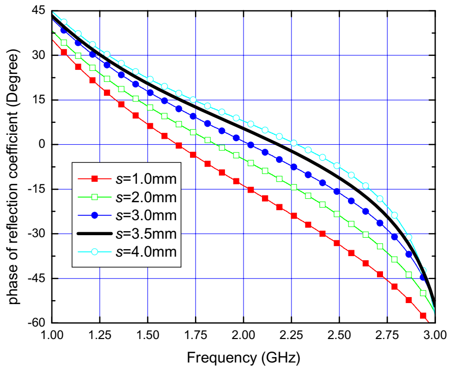


Fig. 5 The influence of the gap s on the reflection coefficient's phase (a=5mm, b=40mm, H=18mm, w=1mm, L=50nH).

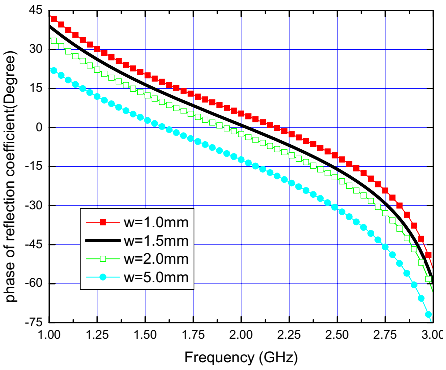


Fig. 6 The influence of the width w on the reflection coefficient's phase (a=5mm, b=40mm, H=18mm, L=50nH, s=3.5mm).

The width of the microstrip line w is one of the variables of the equivalent capacitance, which will get larger with the decrement of w. This width has an effect on the characteristic impedance of the microstrip line as well. It is plotted in Fig. 6 about the influence of the strip width on the phase of the reflection coefficient. It is seen that a wider strip width produces a better result. The relation between the height of cell and the reflection coefficient's phase is shown in Fig. 7. These curves overlap each other below the resonant frequency and then split up quickly as the frequency further increases.

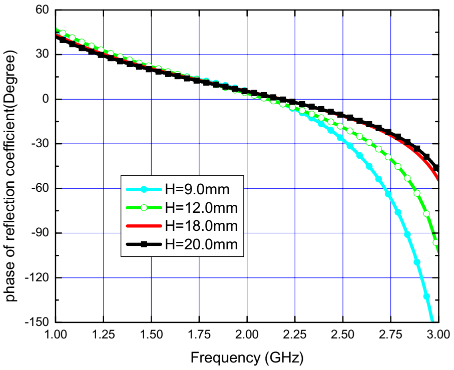


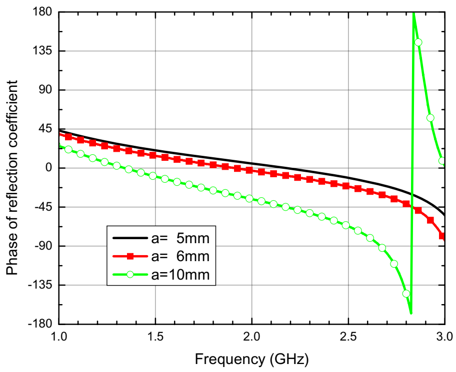
Fig. 7 The influence of the height of cell H on the reflection coefficient's phase (a=5mm, b=40mm, w=1mm, L=50nH, s=3.5mm).

4. Optimized Results

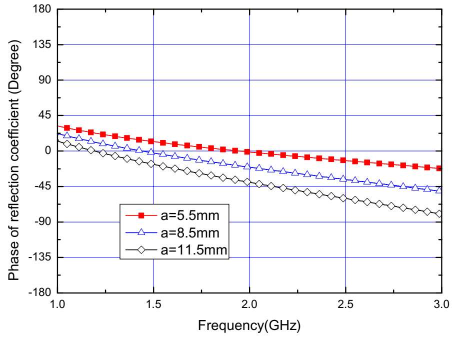
After the adjustment on various parameters, the final result of the reflection coefficient's phase in the one-stage case is illustrated in Fig. 8 (a) under different structure heights. It is seen from this figure that the slopes of the curves are very flat and smooth over the desired frequency range from 1GHz to 3GHz. The phase at the central frequency (2GHz) is only about 5° and its variation is controlled within a narrow range, -45° ~ 45°. The optimal results of the two-stage case are shown in Fig. 8 (b). According to the comparison of equations (5) and (8), the slope of the phase in the two-stage case is smaller than that of the one-stage case. This can be seen in Fig. 8 (b) especially when the height equals to 5mm with about 0° phase in the central frequency. The optimal result demonstrates that the design of the structure is successful for achieving the high-impedance surface of small thickness.

5. Conclusion

In this paper, a novel high impedance structure with lumped components has been presented. To realize the high impedance surface, the simulated phase of the reflection coefficient should be controlled in a very narrow range in the desired frequency range 1GH-3GHz. It has been analyzed that a small series capacitance results in a flat frequency response of the phase. After the variation of the capacitance, inductance and the microstrip width on the simulated phase of the reflection coefficient, the optimized results show that the reflection coefficient's phase has been controlled within a range of -45° ~ 45°over the frequency band 1 to 3GHz both in one-stage and two-stage cases. This high impedance surface of very small thickness should be very useful in designing absorbing materials and designing small antennas of low profile.



(a)



(b)

Fig. 8 HFSS simulated phase of the reflection coefficient
(a) One-stage case (b=40mm, H=18mm, w=1mm, L=50nH, s=3.5mm)
(b) Two-stage (b=20mm, H=12mm, w=1mm, L=150nH, s=1mm).

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