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Low loss three-dimensional metamaterial-based omega-net microwave lens

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Abstract

Straight forward design of a three-dimensional microwave lens operating from the X- to K-band is proposed. Two-dimensional Omega-net structures that proved to have a near-zero refractive index with low loss are used as a startup design, and later are optimized and implemented to construct a three-dimensional near-zero refractive index structure. A 3D single-shell Omega-net lens can generate dual near-zero refractive index bands, 9.16GHz-10.32GHz or 5.32% BW and 11.36GHz- 12.62GHz or 5.25% BW. Other two candidates, i.e., a 3D double-shell Omega-net and a 3D diamond double-shell Omega-net lenses are also introduced.

Keywords: Microwave, Lens, 3D, Refractive index, Near-zero, Metamaterials

1. Introduction

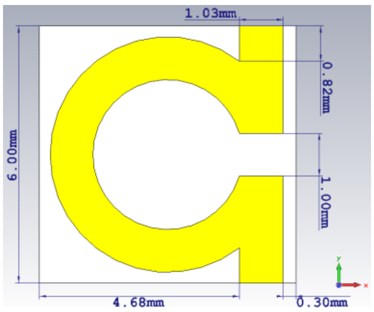
According to the properties of near-zero refractive index metamaterials, the transmitted waves propagating from such materials into air are normal to the interface. Near-zero metamaterials have been designed to be integrated into different kinds of antennas, phase shifters, couplers, and resonators in order to control wave direction [1-3]. Directivity enhancement using a short-focal-length plano-concave lens engineered by a fishnet-like stack with an effective negative index of refraction close to zero has been reported [4]. The pencil-like radiation is achieved by using this near-zero refractive index metamaterial lens.

In this paper, we propose Omega-net structures for our near-zero refractive index metamaterial design. Two-dimensional (2D) Omega-net structures are first optimized to have a broad low-loss near-zero refractive index. Then, utilizing the optimal 2D Omega-net structures, several 3D Omega-net lens designs are derived and implemented.

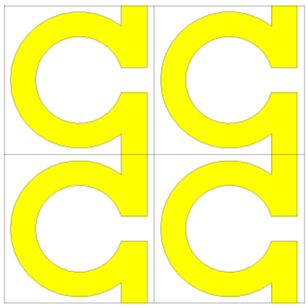
2. Near-zero refractive index 2D Omega-net structure

Omega-net structures are tailored to achieve a near-zero refractive index in microwave regimes. The Omega-net is composed of two bars and a split ring, as shown in Figure 1. The near-zero band results from the overlap of electric resonance generated from the bars and magnetic resonance generated from the split ring. The near-zero-index band is found at the transition from a $-n$ region to a $+n$ region. Both the permittivity and the permeability are controlled via geometrical parameters and structure orientation, and are near-zero within the operating band, resulting in low loss transmission.

Figure 2 shows five cases of 2D Omega-net structures where the location of the two vertical bars are used for controlling the permittivity by varying the location of these bars concurrently beginning from the gap end on the right side (case 1) to the opposite end on the left side (case 5).



(a)



(b)

Figure 1 (a) Unit cell and (a) periodic array of 2D Omega-net structures.

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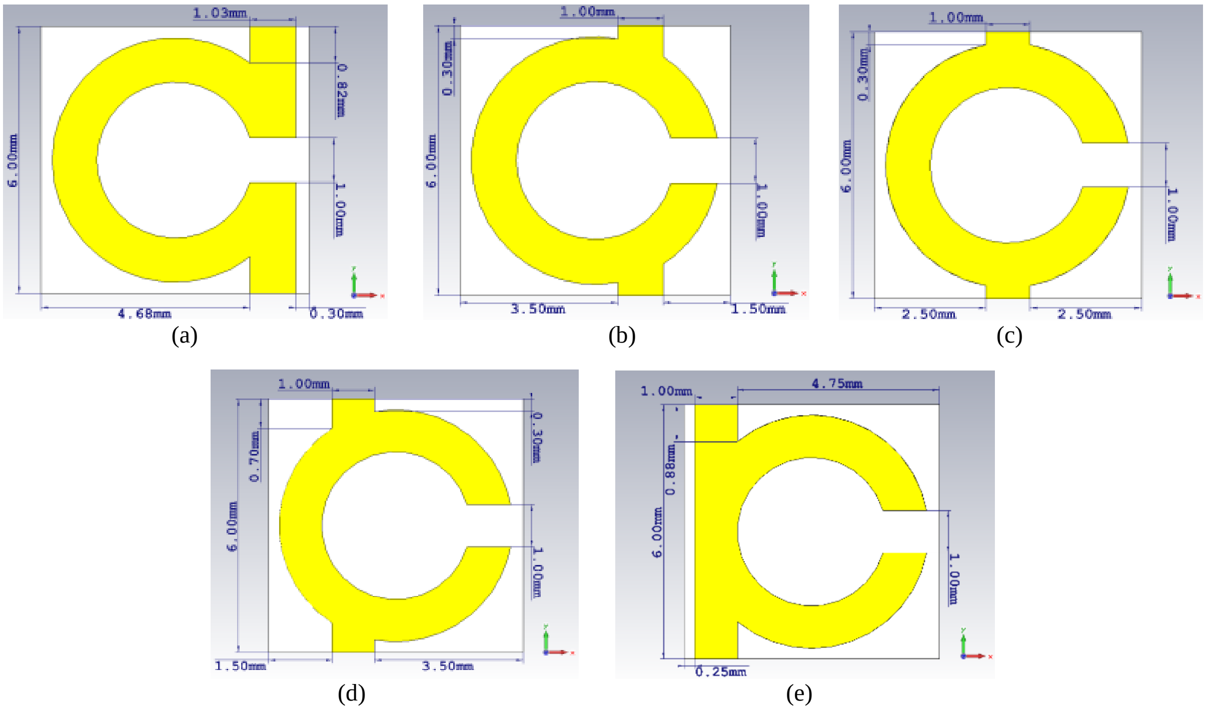
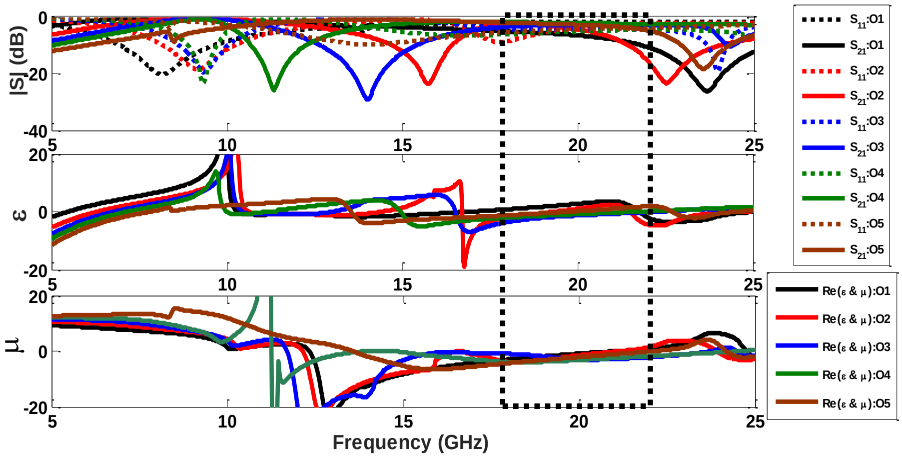
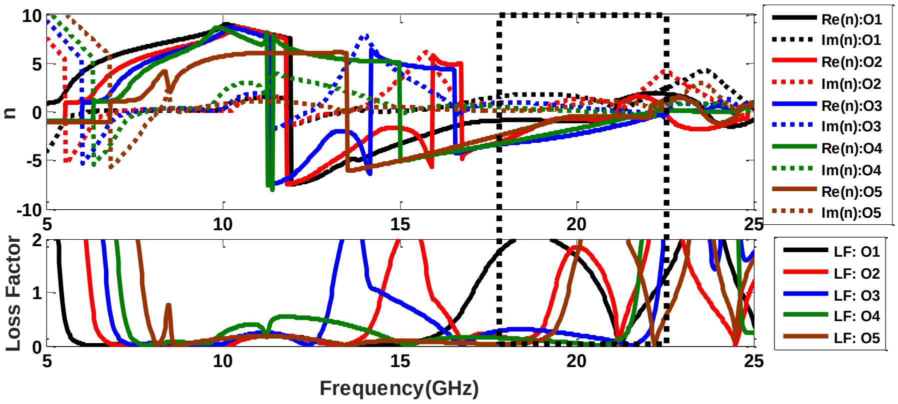


Figure 2 2D Omega-net structure: epsilon-bar variation: (a) case 1: epsilon-bar at right position (b) case 2: epsilon-bar at right-middle position (c) case 3: epsilon-bar at middle position (d) case 4: epsilon-bar at left-middle position (d) case 5: epsilon-bar at left position.



(a)



(b)

Figure 3 Transmission properties and EM parameters of 2D Omega-net structures: (a) transmission coefficient and permittivity/permeability focus area (b) refractive index with low-loss focus region.

Figure 3 shows the transmission properties and electromagnetic (EM) parameters for the five aforementioned cases of 2D Omega-net structures. Good transmission passband, where low permittivity ($\varepsilon \rightarrow 0$) and permeability ($\mu \rightarrow 0$), is indicated by the dashed black rectangular box in Figure 3(a). As expected, a low refractive index ($|LF| < 1$) with a low loss ($n \rightarrow 0$) is found within the same frequency range, also enclosed within the dashed black rectangular box in Figure 3(b). Figure 4 focuses on the low loss, n near-zero band of all five Omega-net cases.

A low loss, n near-zero band is found in all five Omega-net cases. The dashed rectangular boxes indicate the $|LF| <$ 1 and $|n| <$ 1 transmission band where strong normal out-going beams will propagate outward from the Omega-net periodic structures. One n near-zero band is generated in Omega-net case 1 (black box), case 3 (blue box), case 4 (green box), and case 5 (blown box). The n near-zero band is broadest in Omega-net case 4, from 20.8 - 22 GHz or 21.4 % bandwidth (BW), while "dual" n near-zero bands are found in Omega-net case 2, 19.16-19.38 GHz or 1.14% BW and 20.88-21.32 GHz or 2.09 % BW.

The conventional Omega-net structures are then modified in order to lower and broader the low loss n near-zero bands. Figure 5 presents the optimized Omega-net structures. The transmission properties and EM parameters of the 2D hexagonal Omega-net structure are shown in Figure 6.

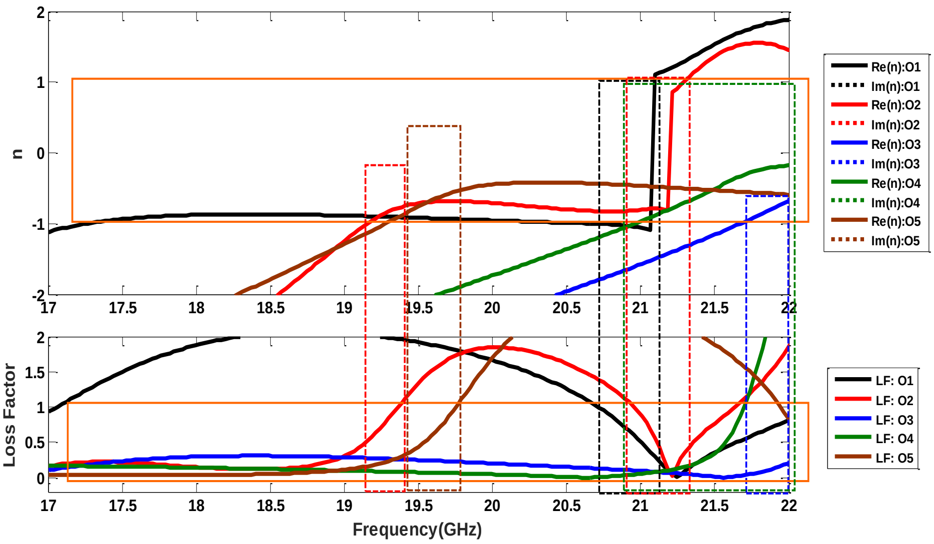
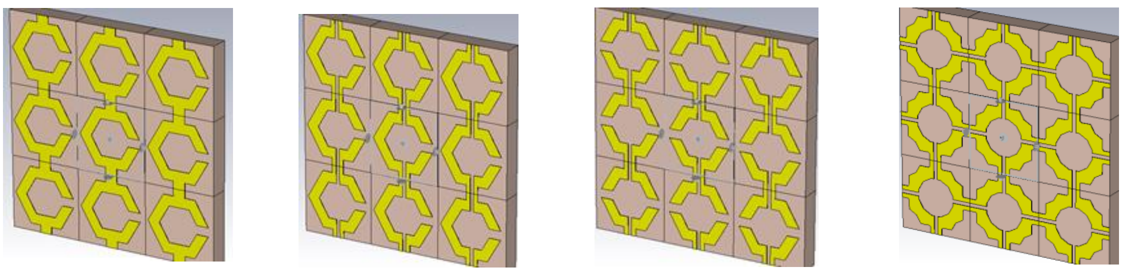


Figure 4 Refractive index and loss factor 2D Omega-net structures focusing on near-zero refractive index with low loss bands



(a) (b) (c) (d)

Figure 5 Optimized 2D hexagonal Omega-net structures.

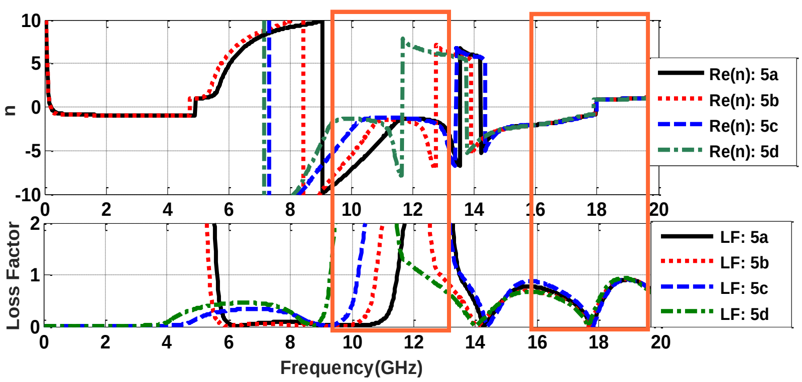


Figure 6 Refractive index and loss factor of hexagonal 2D Omega-net structures.

It can be seen that the low loss n near-zero band shifts to lower frequency. Furthermore, another low loss n near-zero band is found at higher frequency. The two bands are enclosed within the orange boxes.

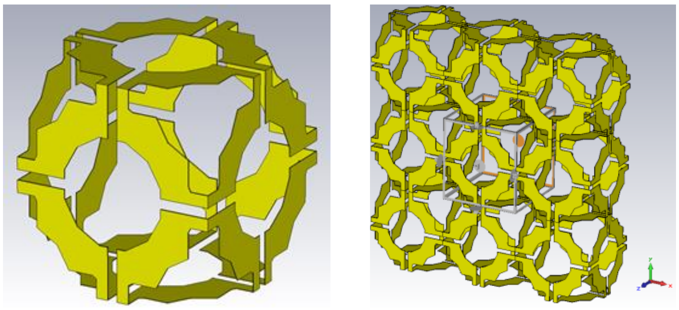
3. Three-dimensional Omega-net lens

The 3D single-shell Omega-net lens presented in Figure 7 is designed for a microwave lens. The dual near-zero refractive index bands, 9.16-10.32 GHz or 5.32% BW and 11.36-12.62 GHz or 5.25% BW are established, as illustrated in Figure 8.

Other two candidates for microwave lens are 3D double-shell Omega-net structures and 3D diamond double-shell Omega-net structures. Their unit cell and periodic sketches are illustrated in Figure 9. Both structures can generate broad "dual" near-zero refractive index with low loss bands: 3D double-shell at 12.24-13.20 GHz (3.77% BW) and 26.24-30.32 GHz (7.21% BW) and 3D diamond double-shell at 10.23-11.07 GHz (7.89% BW) and 15.3-16.14 GHz (5.07% BW).

4. Conclusions

A dual band three-dimensional microwave lens operating from the X- to K-band is proposed. The lens is composed of three-dimensional Omega-net structures, where the near-zero refractive index is effectively manipulated. Several three-dimensional Omega-net structures are introduced. These proposed structures are additional promising candidates for near-zero refractive index metamaterials which will facilitate lens applications.



(a) (b)

Figure 7 (a) Unit cell and (b) periodic 3D Omega-net structures.

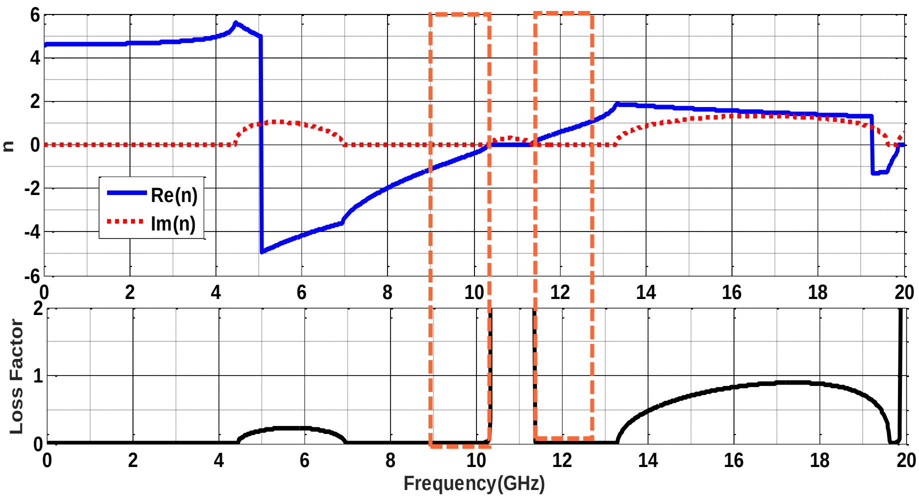
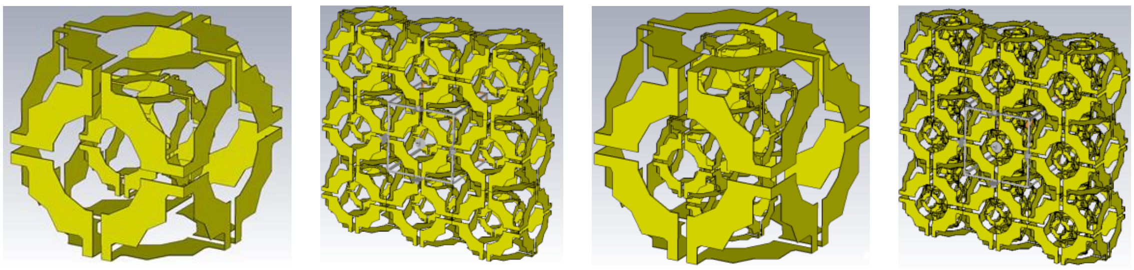


Figure 8 Refractive index and loss factor of 3D Omega-net structures.



(a) (b) (c) (d)

Figure 9 (a) Unit cell and (b) periodic 3D double-shell Omega-net structures. (c) Unit cell and (d) periodic 3D diamond double-shell Omega-net structures.

5. Acknowledgements

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