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Design of a high-sensitivity and high-Q microwave sensor based on H-fractal metasurface structure

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Abstract. This paper proposes a metasurface based on H-fractal unit structure, which exhibits three transmission resonance peaks. The simulation results show that these peaks are very sensitive to samples with different refractive indexes. The biggest frequency shift of these resonant peaks is about 2.6 GHz when the refractive index of samples changes by 1 and the quality factor(Q) values of the second and the third peak are up to 191.55 and 179.40 respectively, which has great application potential in the field of microwave sensing because its high-sensitivity and high-Q.

Keywords: Microwave sensor; metasurface; fractal structure; high-sensitivity; high-Q

1. Introduction

Metasurfaces are artificial composite surfaces that are composed of some units of subwavelength structures arranged in a certain sequence[1]. They have some extraordinary properties that natural surfaces do not have, which make them possible to arbitrarily manipulate various wave physical properties such as light waves, microwaves, radio waves, and sound waves. Metasurface-based microwave sensors are very attractive to researchers for their wide applications in industry, biomedicine and healthcare, because they might have lots of advantages such as higher sensitivity, higher accuracy, and faster speed[2].

Fractal is a typical multi-level composite structure which has unique geometric properties such as self-similarity, cross-scale symmetry and non-integer dimension[3]. So far the research on combination of metasurface and fractal structure has not been very extensive. This paper proposes an H-fractal metasurface structure which has the advantages of multi-peaks, high-quality factor(Q) and high-sensitivity at the same time. It could be employed as high-performance microwave sensor.

2. Design of Structure

Fig. 1 shows the geometrical parameters of the H-fractal unit structure for metasurface. As shown in Fig. 1 (a)(b), the metal of structure is copper(pure) with the thickness of 0.015mm and the substrate is Polyimide(lossy) with the thickness of 0.1mm. The key dimensions of the structure are shown below: the period (p) = 22.00mm, the specific parameters of the first level fractal: l1 = 9.00mm, l2 = 14.00mm, the specific parameters of the second level fractal: l3 = 1.35mm, l4 = 2.10mm. There is an equal proportional relationship between the first level fractal and the second level fractal, which means l1/l2 = l3/l4. The simulation results are based on Finite Integration Technology(FIT). In these simulations, the periodic structure is illuminated by a normally incident electromagnetic wave with electric field parallel to the x-axis.

According to Faraday’ s law, when a time-varying magnetic field component is perpendicular incident on the H-fractal unit structure, electromagnetic-resonance will be generated. The whole structure can be represented by an equivalent LC-circuit and the equation (1) gives the resonant frequency[4].

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$$f = 1/\sqrt{2\pi(LC)} \quad (1)$$

When the H-fractal metasurface structure is employed as microwave sensor, the equivalent electromagnetic parameters of the metasurface structure will change along with the refractive index changes due to the sample to be tested. According to the equivalent LC circuit model, these changes will cause the shift of resonant frequency and the amplitude of the transmissivity.

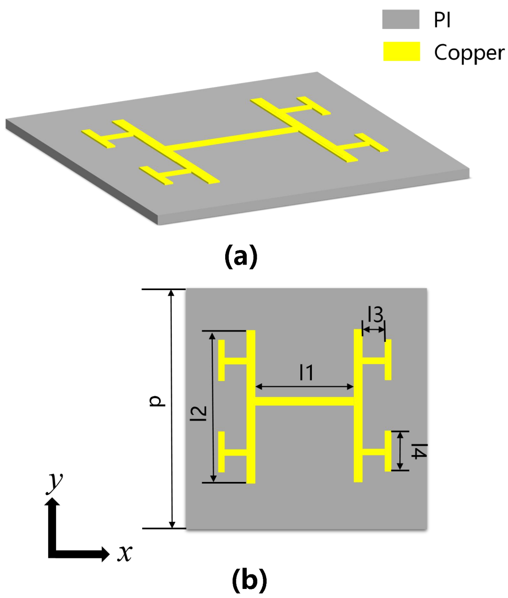

Fig. 1 (a) Structure of the unit cell of the H fractal (b) The geometrical parameters of the H-fractal unit structure

3. Simulation Results and Analyse

Fig. 2 shows the transmission spectra of different H-fractal levels. It can be seen from Fig. 2(a) that the first level fractal consists of three discrete transmission resonance peaks at 10.52 GHz, 13.72GHz and 19.00 GHz (n=1) respectively. From the Fig. 2(b), the three discrete transmission resonance peaks are at 9.16GHz, 13.60GHz, and 18.48GHz(n=1) respectively for the second level fractal. Comparing to the first level, the transmission resonance peaks have a little red-shift because the effective electric length of the structure will increase with the level of the fractal increases[5]. According to the equivalent LC circuit model, the resonance frequency of the metasurface is inversely proportional to the length of the metallic pattern, which leads to the red-shift.

Table 1. Q value and sensitivity of proposed structure

The structure	The second peak		The third peak	
	Q	Sensitivity (GHz/RIU)	Q	Sensitivity (GHz/RIU)
First level fractal	75.80	1.20	441.80	1.76
Second level fractal	191.55	1.20	179.40	2.60

The Q value is a dimensionless parameter that describes how underdamped an oscillator or resonator is. It is defined as Q = f / FWHM, where f is the resonance frequency of the transmission peak[6]. The higher the Q value, the sharper the resonance peak, and the easier it is to identify the resonance frequency there. So it is an important indicator for evaluating the performance of a sensor.

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Sensitivity(S) is another important indicator to evaluate the performance of a sensor which is defined as S = df / dn, where df is the frequency offset and dn is the refractive index change. Based on the simulated results of Fig. 2(a) and Fig. 2(b), the Table I shows the Q value and sensitivity of the two level fractal structures, from which we can see that for the second level fractal structure, the Q value increases from 75.80 to 191.55 for the second peak and the sensitivity increases from 1.76 GHz/RIU to 2.6 GHz/RIU for the third peak. Although the Q value of the third peak of the first level fractal is larger than that of the second level fractal, the third peak of the first level fractal is hard to be detected when n = 2. Through the comparison, the second level fractal has a superior performance in the quality factor and sensitivity, which makes it great potential as microwave sensors in the future.

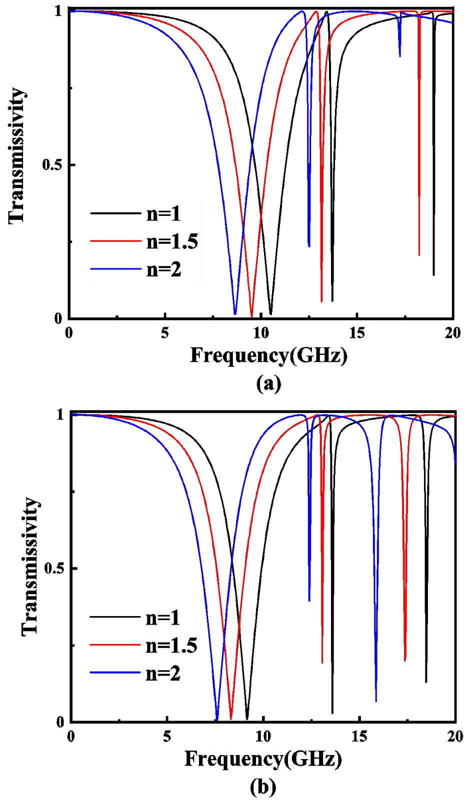

Fig. 2 (a) The transmission spectra of the first level fractal; (b) The transmission spectra of the second level fractal.

The schematic diagram of the proposed microwave sensor for detecting samples with different refractive index and its deployment are shown in Fig. 3. All the experiments will be carried out at a room temperature. In our measurement, signal is generated by vector network analyzer (AV3672C, 10MHz - 43.5GHz), and a pair of antennas are used to transmit and receive signals[7].

In order to evaluate the performance of the proposed sensor, samples(thickness is 0.5mm) with different refractive index ranging from 1 to 2 are simulated. The simulated results shown in Fig. 4 illustrates that all three resonant peaks have large frequency shifts especially the third peak, which has sensitivity of 2.6GHz/RIU. From the Table I, the Q value of the third peak is 179.4, which makes the third peak high-sensitivity as well as high-Q.

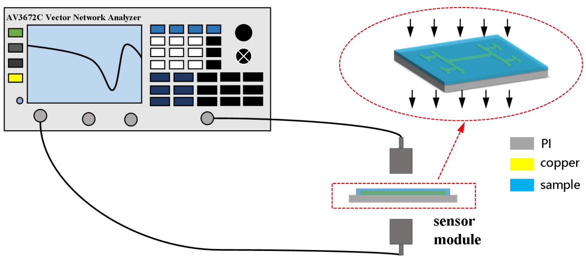

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Figure 3. The schematic diagram of the proposed microwave sensor for detecting samples with different refractive index.

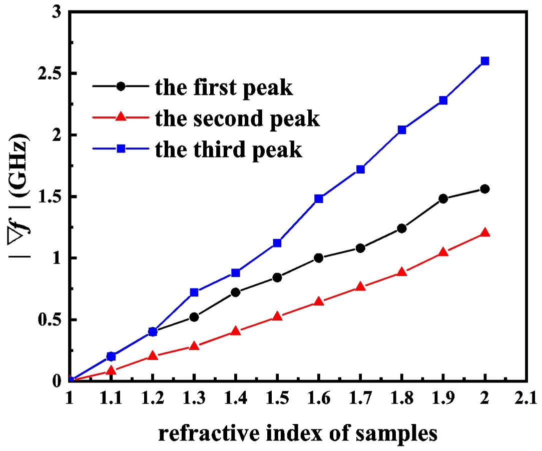

Figure 4. Simulated results of the metasurface microwave sensor in detecting different samples with refractive indexes.

4. Conclusion

The paper presents a novel and simple design of a metasurface based on H-fractal structure. In contrast to most previous studies, the second level fractal design could meet the advantages of multi-peaks, high-Q and high-sensitivity at the same time, which makes the metasurface great potential as microwave sensors.

Acknowledgment

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