New fractal structures for frequencies close to the visible range

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Abstract

In this paper we present a new type of fractal resonator to be used in the red/NIR region of the spectra. The structure presents high-transmission band in 795-825nm range. The stop band is in the 683-731 nm range. Due to the huge difference in the spectra within such a short range, the structure can be used as an efficient sensor, both in transmission as well as in reflection. Thus, a variation of only 0.09 in the refraction index will for example change the structure's behaviour from 90% reflection to 90% transmission. Such resonances lead to a sensitivity of 780 nm/RIU. Another advantage of this resonator is the independency of the incidence angle - in the spectral region of interest; the incidence angle has very little influence over the response.

1. Introduction

In the last years the use of metals in optics has been seen in a new light due to advances in theory and modelling of metal-dielectric structures. Such structures promise a lot of new applications like super-resolution lenses, bio-sensors, invisibility cloaks, possibility of studying phenomena like black holes behaviour or inter-atom interactions in a broad wavelengths range from the THz and far infrared up to ultraviolet. Metal-dielectric structures allow obtaining effective properties not yet encountered in nature. This stimulates the emergence of a new boosting field of metamaterials (MMs) [1, 2] which is mentioned in "*Science*" among 10 insights of the first decade of the XXI century [3]. Using such structures it has been proven that one can obtain lenses that image far beyond the diffraction limit or magnetic response at optical frequencies completely ignored before [4]. The MMs have triggered a new field called transformation optics [5-8] that allows engineering the space properties so that the light travels on prescribed paths, even backwards.

One of the new possibilities in applying the metamaterials concepts is by using fractal structures [9, 10]. Such structures combine the advantages of the photonic crystals with the ones of frequency selective surfaces [10] thus allowing for e.g. obtaining high selective reflection using small components. Typically, fractal metamaterials have been reported in microwaves or THz. In this paper we present the optical properties of the new type of red/near IR fractal resonator, designed aiming at fabrication possibilities.

2. Proposed fractal resonator

The way we decided to approach the fractal generation problem is fabrication-wise. Since due to fabrication process structures will inevitably have rounded corners, we chose to implement instead of the rectangular or angled structural elements, circular ones. Therefore, we consider our fractals to be built with circular architecture.

The fractal is defined, from mathematical point of view, as follows: we consider a circular disk of radius R, having the origin in the point $O(0,0)$. From this disk we cut out sub-disks of radius $r = 2R/9$, having the origins in the points $C_k((2R/3)*\cos(k\pi/3), (2R/3)*\sin(k\pi/3))$, k=1,2…6 (see Fig. 1(a)). The process described is restarted for the sub-disk with the center $O(0,0)$ and the radius $R_1 = R/3$

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(see Fig. 1(b)) and then for the sub-disk with the center $O(0,0)$ and the radius $R_2 = R_1/3$, (see Fig. 1(c)) and so forth. By continuing in this way ad infinitum we obtain a central distributed circular fractal.

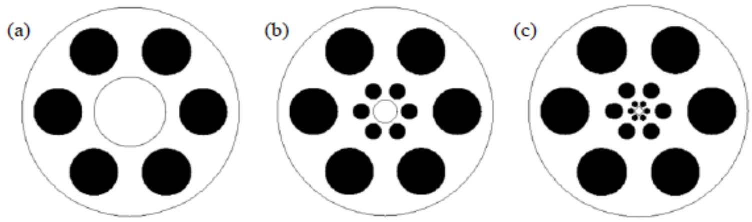

Figure 1: Generation of circular pre-fractals of the first (a), second (b) and third (c) order.

In practice, the generation of the fractal structure will end when the dimensions of the smallest structural element reach the resolution limit in the chosen fabrication chain. The pre-fractal obtained this way will be defined by the dimension of the biggest disk and the fractal order that is, the number of times the algorithm is repeated recursively.

Since a dimension that can be reproducibly achieved with standard electron beam lithography is 100nm, we decided the smallest disk to be of 100 nm in diameter. Also, we have chosen the pre-fractal of the second order thus having a disk of radius R = 675 nm as the basic unit cell. By following the generation process of the fractal presented earlier, at step 1 the 6 peripheral sub-disks have radius r = 150 nm. Then, we apply step 2 to the central disk of radius R_1 = 225 nm, from which we remove again 6 sub-disks. These sub-disks have radius r_1 = 50 nm. The material the unit cell of the structure studied in this paper and presented in Fig. 2 is a square-form metallic membrane having the sides of 1350 nm and the thickness of 30 nm.

The simulations were performed using the CST Microwave studio. The system is thought as a periodic structure with the period of 1350 nm. Each unit cell is composed of the aforementioned pre-fractal. The metal is considered a Drude metal with plasma frequency $1.39269 \cdot 10^{16}$ rad/s and collision frequency $2\pi\ 1.684 \cdot 10^{13}$ Hz. The simulation range extends from 150 to 600 THz and, in order to simulate an infinite periodic structure we imposed PML boundaries in the direction of propagation and unit cell boundary conditions in the fractal plane (see Fig. 2).

3. Simulation results

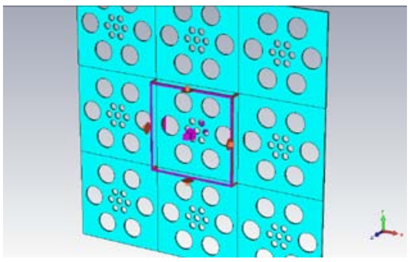

Figure 2: Overview of the simulated structure.

The simulations show a transmission band centred at 810 nm and having 30 nm bandwidth (see Fig. 3(a)). In the same region the reflected signal being less than 0.1 suffers a cute π phase shift (see Fig. 3(b)). Using these characteristics, one can design a filter that will measure the change in the surrounding refractive index e.g. by the change in the transmission value at a certain frequency. In Fig. 3(c) the change in the transmission amplitude can be seen when the refraction index in the holes changes from 1 to 1.14 in steps of 0.02. A step of 0.01 can be easily discerned but not shown for clarity of the figure. As a competitive alternative the shift in the resonance in the phase spectra (see Fig. 3(b)) can be used.

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The S parameters characteristics are held within a big angle of incidence range (see Fig. 3(d)). This independency with respect to the incidence angle allows the easy positioning of the sensor. This way the errors due to aligning in the measuring setup are decreased. Also, there are fewer design issues for such type of sensors.

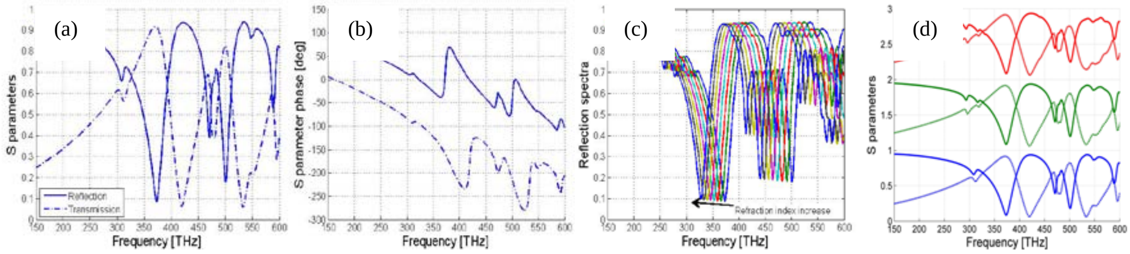

Figure 3: (a) Amplitude and (b) phase of the reflected and transmitted signal at normal incidence. (c) Amplitude of the reflected signal when the refraction index varies from 1 (rightmost spectra) to 1.14 (leftmost spectra) with a 0.02 step. (d) Simulated spectra at 10, 20 and 30 degrees incidence angle. The spectra are shifted for better viewing

4. Conclusion

In this paper we have presented a new type of fractal resonator feasible for reproducible fabrication, which shows enhanced transmission at 810 nm wavelength. Such structure can be used for various purposes, the one highlighted in this work being sensing. Thus, using the proposed structure a two range sensor can be used. On one side, by measuring the amplitude spectra one can determine big variations in the refractive index. Variations in the order of 1% can be measured this way. The theoretical sensitivity is 780 nm/RIU, which is one of the highest sensitivity values obtained using optical devices. For comparison, the best photonic crystal sensitivity reported so far is in the order of 550 nm/RIU [11]. On the other side, the measure of phase shifts gives the possibility of discerning among very slight variations of the refractive index. Using the phase resonance one can measure variations of the refractive index down to 0.1% (a phase variation of 10 degrees being equivalent to 1% variation in refractive index). The simulations show high independency of reflection-transmission characteristics with the incidence angle in the frequency range of interest.

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