Transmission Properties of Subwavelength Planar Fractals for THz Wavelengths

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ABSTRACT

We investigate the transmission properties of planar H-fractal structures in THz range. 3D EM simulations using HFSS are used to design the parameters of the fractals and to evaluate the optical properties. We observe the transmission spectra with pass bands and stop bands, which show the subwavelength transmission through the non-metallic gaps. This unique transmission property through subwavelength apertures makes it potentially useful frequency selective components in THz region. We experimentally demonstrate its behavior by designing and fabricating four prototype planar fractals in the range of 0-1.5THz and characterize using a polarizing Fourier transform spectrometer. We find good agreement between the models and measurements.

INTRODUCTION

The electromagnetic transmission properties through subwavelength apertures have attracted increasing attention due to the potential applications as frequency-selective components (FSS) in the development of terahertz optoelectronics. Extensive experimental and theoretical work has been carried out to analyse the physical details of the transmission process. The phenomenon of enhanced transmission through the metallic film with periodic arrays of subwavelength holes was first reported by Ebbesen in 1998 [1]. Later Qu presented the experimental result of the transmission magnitude and phase change of terahertz pulses through thin metallic films patterned with subwavelength hole arrays on silicon wafers [2]. In 2002 Wen presented by both experiment and theory that a specific class of planar conducting fractals can exhibit multiple stop and pass bands over a broad microwave frequency range, with the desired property that the fractal patterns can be significantly subwavelength in dimensions [3]. More recently optical transmission properties of subwavelength planar fractals in terahertz frequency region were studied experimentally by means of time-domain spectroscopy (THz-TDS) [4, 5, 6]. It showed that the frequency gaps corresponding to wavelengths can be significantly larger than the size of the sample; this makes planar fractals a possible potentially useful frequency-selective material. Zhao attributed the detected transmittance from subwavelength fractals to localized resonances.

Followed the experimental work done by Zhao [4, 5], in this paper, we investigate the performance of the planar fractals as a potential band pass/stop filter. In Section 2 we present a theoretical analysis to obtain a physical insight into the behavior and to show how the geometrical parameters relate to its performance. We also present the design parameters of four patterns and expected performance in the 0-1.5THz region. The modeling uses a commercial finite-element analysis package, the high frequency structure simulator (HFSS) [7]. In Section 3 we describe the device manufacture, the measurement and the discussion of the results. The components were fabricated at Cardiff using photolithographic process to produce the patterns in a thin copper layer on a thin dielectric membrane support. Spectral measurements were made using a polarizing Fourier transform spectrometer (pFTS) which enabled the polarisation properties of the structures to be investigated. The measured results are compared with predictions from HFSS. We find good agreement between the models and measurements.

THEORY AND MODELING

Essential Parameters in the Build

Figure 1 shows a basic seven level structure of the non-metallic fractal gap patterns. The patterns have an H-shaped generator, a geometrical scaling factor of 0.5, with no self-intersections. The pattern is generated from a line of length *a* parallel to the *x*-axis in the *xy* plane, defined as the first level of the structure. The k^{th} level of structure of the pattern contains $2k$-1 lines, with the midpoint of each perpendicularly connected to the ends of k-1 level lines. The length of the $(k+1)^{th}$ level lines is scaled from the k^{th} level lines by a factor of 0.5 if the k^{th} is an even number; the length is the same as the k^{th} lines if the k^{th} is an odd number. As the number of levels N tends to infinity, the structure eventually becomes a space-filling curve that tiles a $2a\times 2a$ square (g=2a).

High Frequency Structure Simulator Simulation Result for Fractal Patterns

To explore the optical properties of the fractal structures with different number of fractal levels, we perform analysis based on 3D EM simulations using HFSS and compare these results to measurements of fabricated components (in next section). For these simulations we fixed the first level line's length, *a*, to be 120μm. The grid periodicity (cell size), *g*, to be 240μm. The line width *w* fixed at 6μm. The simulation were made for a range of fractal levels from 4, 5 and 7, as shown in Figure 2(*b*),(*c*) and (*d*). The combined three-dimensional model (7-level) for HFSS simulation is shown in Figure 3, the grid is deposited onto thin substrate 0.9μm thick mylar. The transmission spectra for 4,5, and 7 levels' fractal patterns is shown in Figure 4 (dashed lines), the incident radiation is polarized with its electric field, *E*, perpendicular to the first level line *a* (*x*-axis). Figure 5 shows the transmission spectra with the incident radiation's electric field parallel to the first level line *a* (*x*-axis, dashed lines).

For the electric field *E* perpendicular to the first level line *a* (*x*-axis), we can observe from Figure 4 that the resonant frequency located at 275GHz for the 4-level fractal, the resonant frequency shifted to lower frequency when the number of levels increased, it located at 230.1GHz for the 5-level fractal and reached 170.1GHz for the 7-level fractal. For the higher pass band the similar shift can be observed. The resonant frequency shifted from 1025GHz (for 4-level), shifted to 755GHz (for 5-level), and then down to 455.1GHz (for 7-level). For the electric field parallel to the first level line *a*, from Figure 5, the similar phenomenon can be seen that the resonant frequency located at 500GHz for 4-level fractal, then shifted to 395GHz for 5-level fractal, and shifted further down reaching 290GHz for 7-level fractal. When increasing the fractal level, the capacitance and inductance are effectively appended at both ends of the line, thus tuned the resonant frequency to lower frequencies. This shift with increasing fractal level provides an advantage for making small subwavelength resonant structures [6]. An empirical formula for the resonance wavelengths of an *N*-level fractal structure has been presented by Wen [3], which also proved that the direct consequence of the formula is that the resonance wavelength can be much larger than the sample size. This subwavelength property means that the planar fractal arrays can act as a potential band pass/stop filter.

We also simulated the dependence of the transmission characteristics on the grid cell size (*g*), we scaled down original 4-level patterns (*a*=120μm, *g*=240μm, *w*=6μm) to the quarter of the cell size (*a*=60μm, *g*=120μm, *w*=3μm), as shown in Figure 2(*a*). The transmission spectra for these two 4-level patterns are shown in Figure 4 with incident wave polarized perpendicular to the first level. As expected the resonant frequency shifted to higher band when we scaled down the pattern. The resonance shifted from 275.1GHz up to 500GHz. In Figure 5 (the transmission spectra with incident wave polarized parallel to the first level), the resonance shifted from 500GHz up to 950GHz.

MEASUREMENTS AND DATA ANALYSIS

Manufacture

Fabrication of the prototype fractal patterns follows steps used in the manufacturing of far-infrared low-pass filters [8]. In summary, a photolithographic process is used to produce the metal mesh patterns in copper (~50-100nm) deposited onto thin substrates (0.9μm thick mylar).

Measurements of the fractals

To measure the transmission spectra of the fractals, we used a polarizing Fourier transform spectrometer (pFTS). The schematic drawing of the measurement configuration is shown in Figure 6. Briefly, the pFTS has simply a converging/diverging beam with $f_{\#}$=3, angles $\theta<8^0$. The maximum range of incident angles is then limited by the input source aperture of the pFTS mercury arc lamp source (10mm), a beam spread of only 1.6^0. Further, the fractals are placed centrally in the beam focus section between two polarizers placed at a distance such that they can be easily tilted with respect to the optical axis, to avoid standing wave effects. The efficiency of these polarizers was separately determined to exceed 99.8% over the range of frequencies of interest (50-1500GHz) with a cross polarization of less than 0.1%. The polarizers are aligned with respect to each other with the fractals' first level lines parallel and are also aligned with respect to the optical bench in order to avoid any projection effect when tilted. The more detailed similar measurement set up is described in previous work [9, 10, and 11].

All data were recorded with a spectral resolution of ~1.5GHz set by the pFTS optical path difference. The transmission spectra are obtained by ratioing the sample spectra against the background spectra to determine the fractals response alone [9, 10, and 11].

The polarization axes positions with respect to the fractals has been identified using the same method described in [9, 10], the fractals was placed to the perpendicular and parallel positions, as shown in Figure 6(top part). The transmission spectra of 4(two patterns with *a*=60μm and *a*=120μm), 5, 7-level fractals are measured. Figure 4 shows the transmission with incident wave was polarized perpendicular to the first level line, transmission of polarized parallel to the first level line is shown in Figure 5. We found good agreement between the modeling and the measurements.

CONCLUSIONS

We investigate the electric resonant characteristics of planar H shaped fractal arrays in the 0-1.5THz regime. We found that the lower frequency pass/stop bands correspond to significantly longer wavelengths than the lateral dimension of the fractal patterns. The resonant frequency tuned to lower frequencies when increasing the fractal levels as the effective capacitance and inductance are appended. This subwavelength property shows that the planar fractal arrays can act as a potential band pass/stop filter.

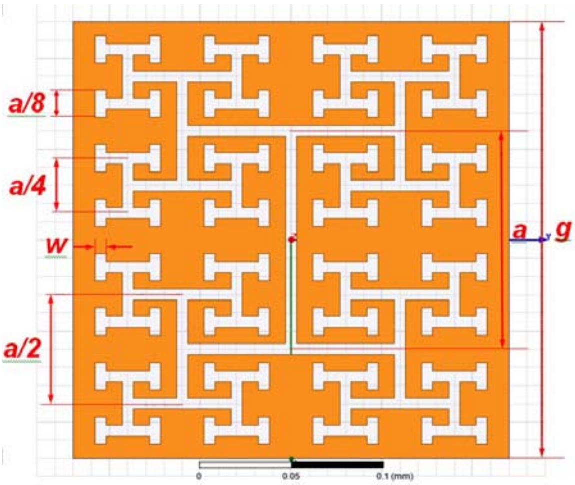

Fig 1: Top view of the basic structure of fractal patterns. The first level line of length a parallel to the *x*-axis. *g*=2*a* is the periodicity.

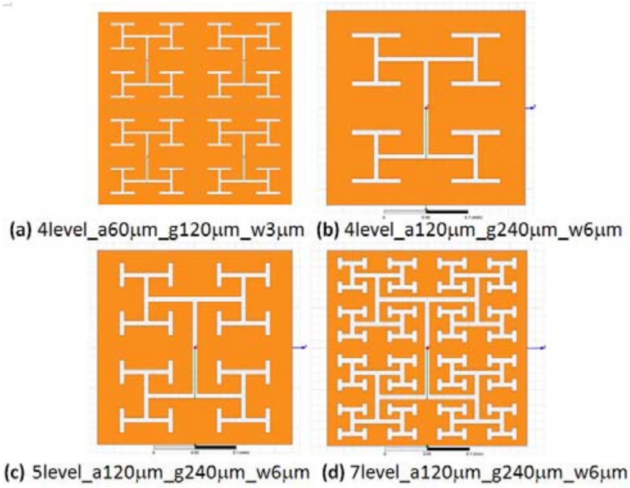

Fig 2: Top view of four fractal patterns.
(a)4-level, first level *a*=60μm, periodicity *g*=120μm, line width *w*=3μm.
(b)4-level, first level *a*=120μm, periodicity *g*=240μm, line width *w*=6μm.
(c)5-level, first level *a*=120μm, periodicity *g*=240μm, line width *w*=6μm.
(d)7-level, first level *a*=120μm, periodicity *g*=240μm, line width *w*=6μm.

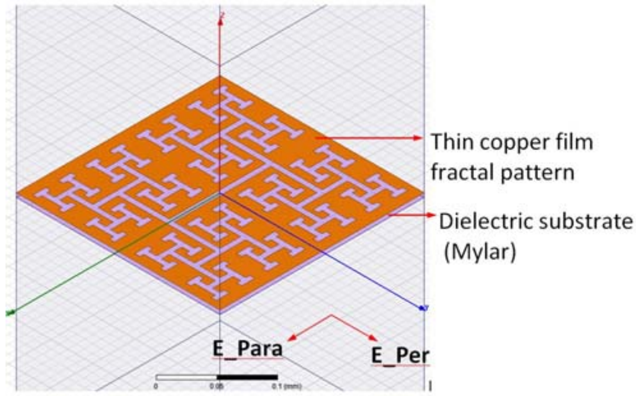

Fig 3: HFSS fractal pattern grids model. The evaporated Cu created photolithographically is typically 0.05-0.1μm thick.

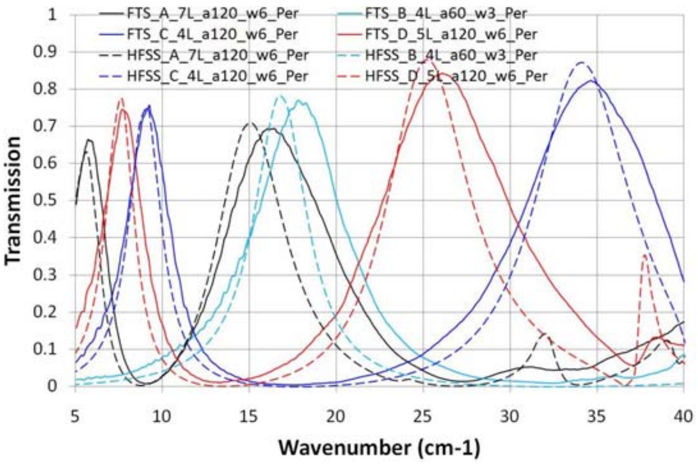

Fig 4: Transmission for four fractal patterns with electric field polarized perpendicular to the direction of the first level line: FTS measurements (solid lines), HFSS simulation (dotted lines).

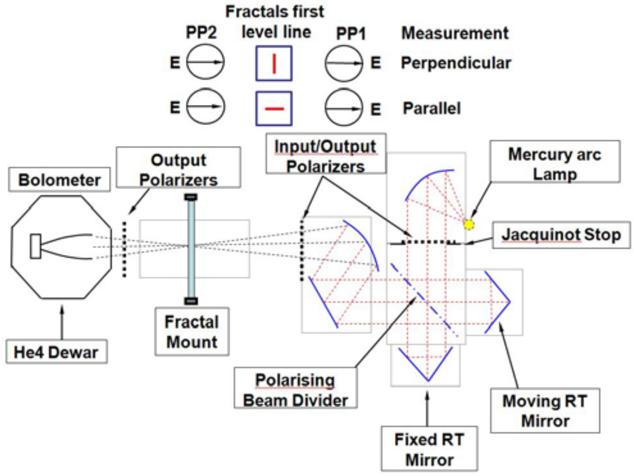

Fig 6: Schematic drawing of spectral measurements setup.

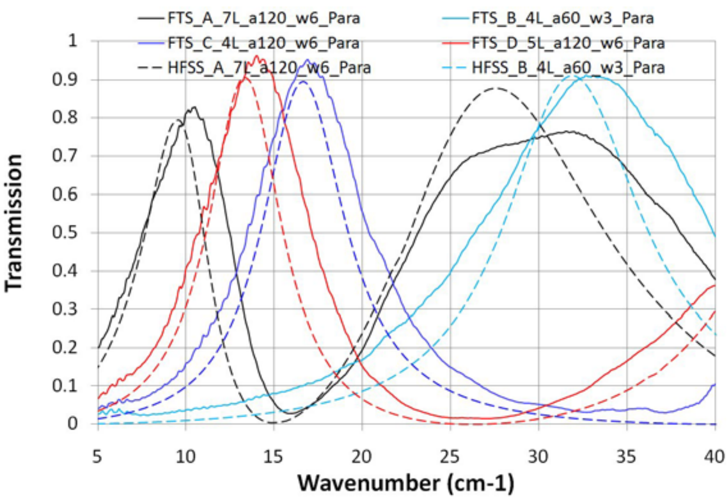

Fig 5: Transmission for four fractal patterns with electric field polarized parallel to the direction of the first level line: FTS measurements (solid lines), HFSS simulation (dotted).

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