Fractal Metasurface Absorbers with Octave-Spanning Bandwidth

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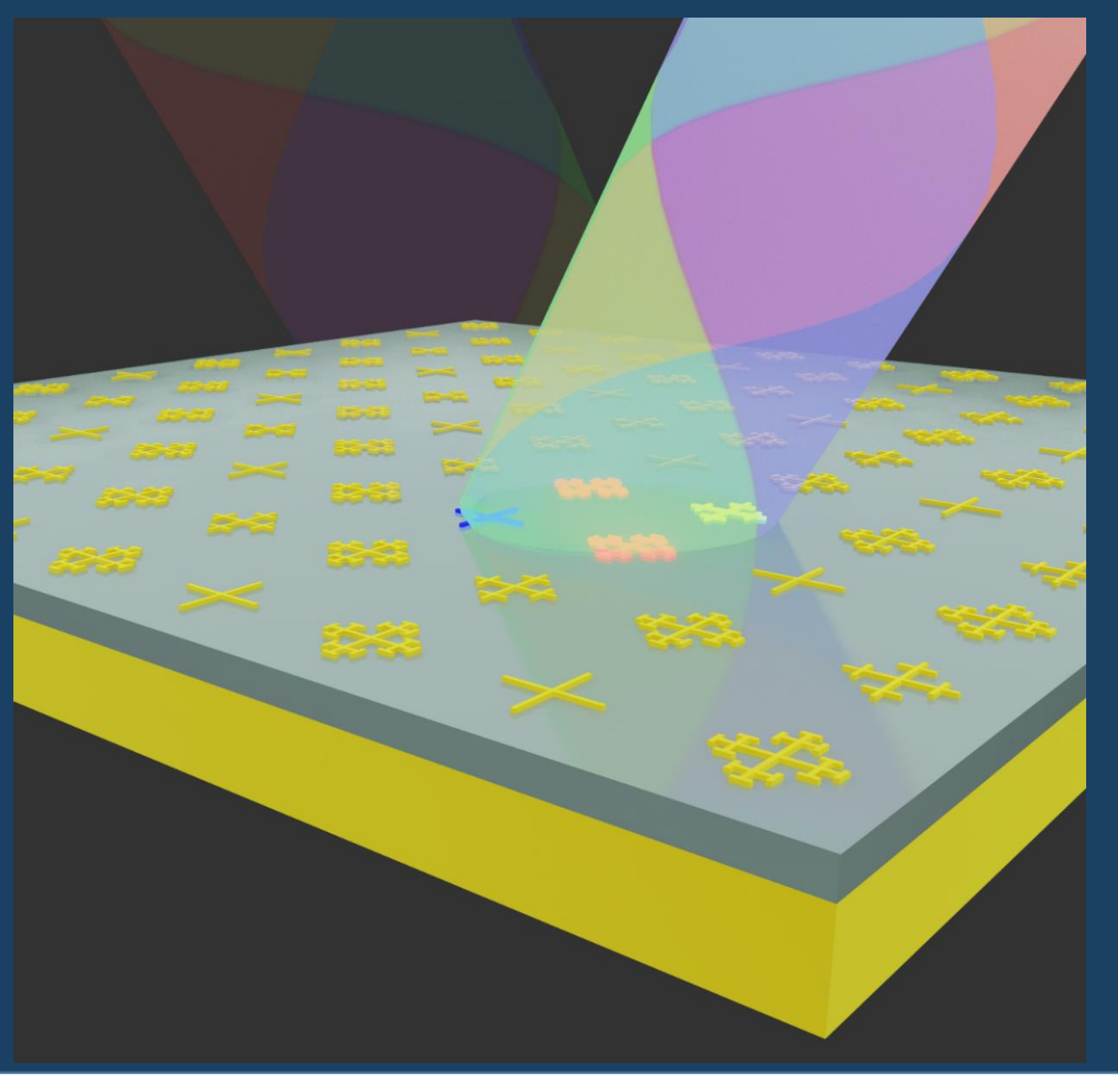


Outline

Synthetic fractals offer a degree of freedom for varying resonance frequency, and are an ideal candidate for broadband absorbing devices – especially in the terahertz (THz) band where there is a lack of naturally absorbing materials. Metasurface absorbers often suffer from poor broadband performance, whilst strongly-absorbing broadband devices are typically complex multilayer structures **[1,2]**. Here, we overcome this limitation by developing an ultra-broadband metasurface absorber based on fractal cross resonators **[3]**, capable of experimentally achieving one *Optical Octave* bandwidth and peak absorption of 93%. We attribute this to a novel absorption mechanism based on both Salisbury screen and anti-reflection responses. Such work is beneficial in realising THz blackbody absorbers, and for bolometric sensing capabilities.

Fractal Absorber Properties

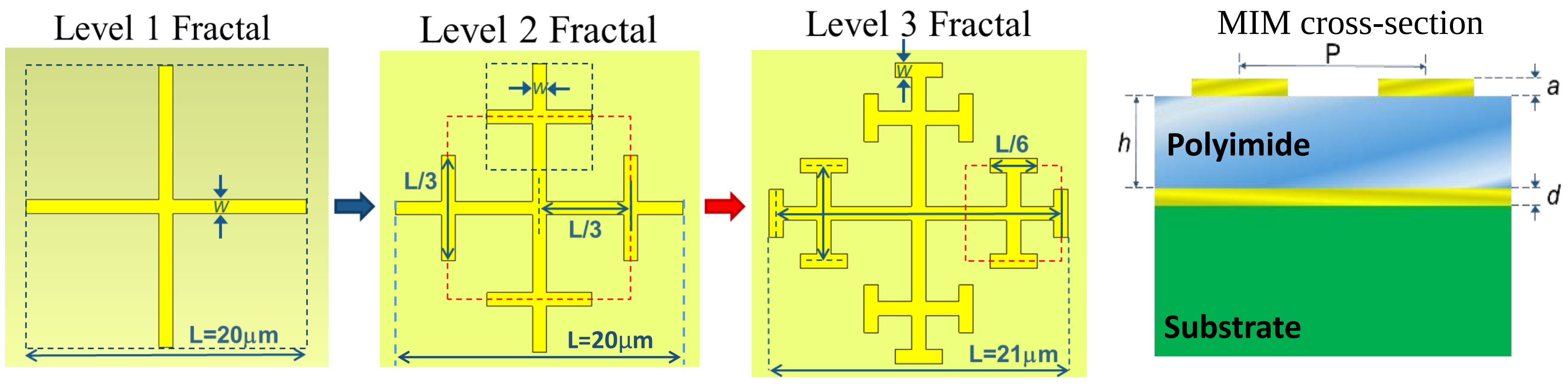
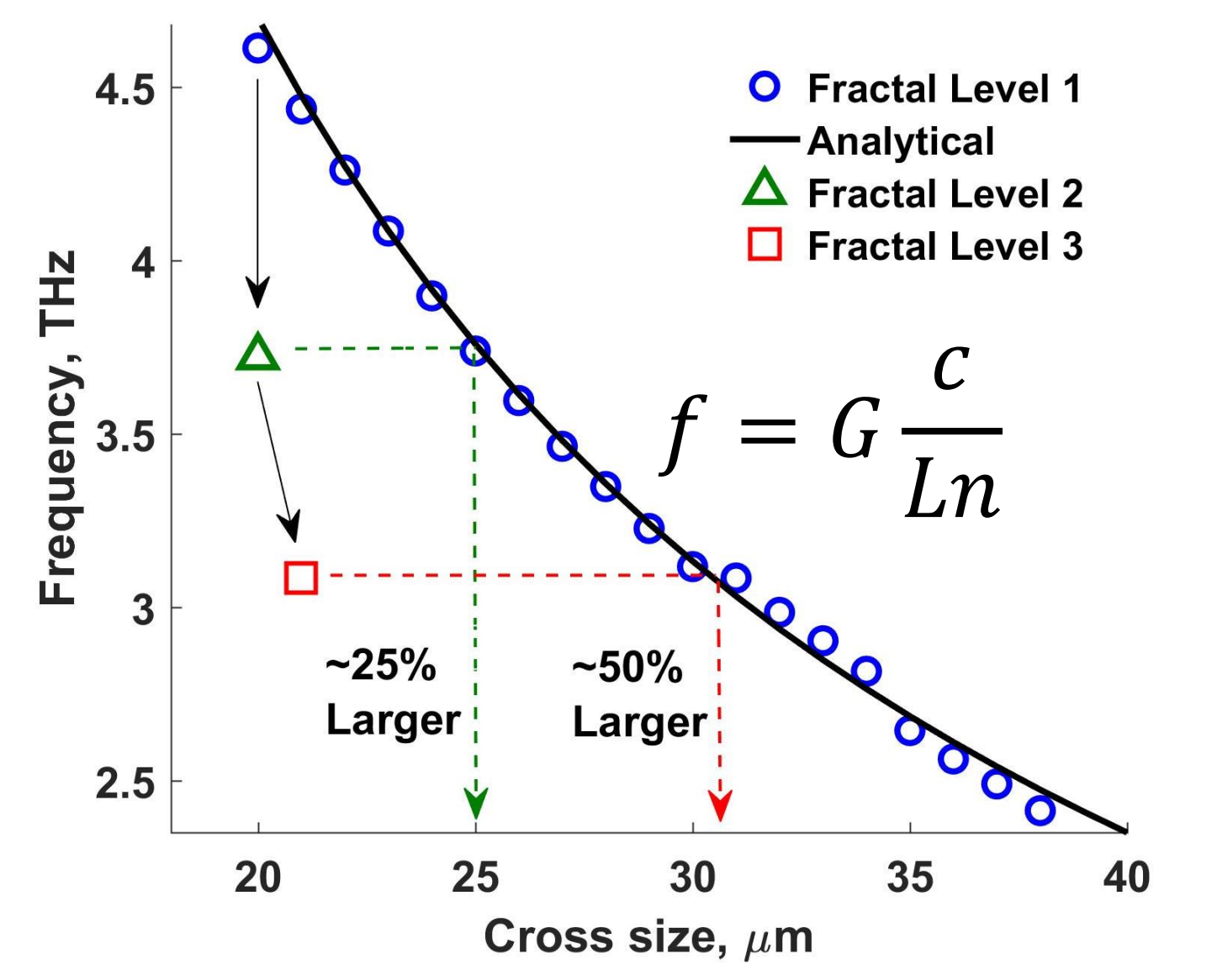


Fig. 1 – Left: Fractal crosses level 1 to 3. Arm-width w = 1 μm. **Right**: Metal-Insulator-Metal (MIM) stack, consisting of gold ground-plane, polyimide interlayer, gold crosses. P = 40 μm, a = d = 100nm, h = 5/11 μm.

The standard **Metal-Insulator-Metal (MIM)** (**Fig. 1, Right**) metamaterial absorber is well studied **[1,2]**. Resonant crosses (**Fig. 1, Left**) coupled to the metallic ground-plane at a certain spacing produce a narrowband absorption (**Fig. 3a**).

Scaling of the crosses results in a resonance frequency shift, as shown in **Fig. 2** (blue circles). An analytical fit relating resonance frequency with cross size is shown (black curve and equation *f*), where *f* is frequency, *c* = 3 x 10^8 ms^{-1}, *L* is cross length, *n* is refractive index of spacer, and G = 1.9 is a coupling coefficient.

Instead, we can achieve a resonance shift by using ***fractal orders*** – where fractals work by increasing the effective electric length of the resonator, offering a new degree of freedom. The above (**Fig. 1**) fractals were chosen, and simulated (Fig. 2 and Fig. 3). We can see in Fig. 2 that fractal levels 2 and 3 equate to standard crosses of ~25% and ~50% size increases, respectively. Also, with an **increase in dielectric thickness**, we witness a **shift from narrowband (Fig. 3a) to broadband** absorption (**Fig. 3b**). We attribute this to a ***novel mechanism*** based on **Salisbury Screen (SS)** and **anti-reflection (AR)** operation (**Fig. 3d**), distinct from the magnetic dipole mechanism **(Fig. 3c) [3]**.



$$f = G\frac{c}{Ln}$$

Fig. 2 – Analytical and simulated size-dependent absorption frequency of simple cross. Higher order fractals can be compared to larger simple crosses.

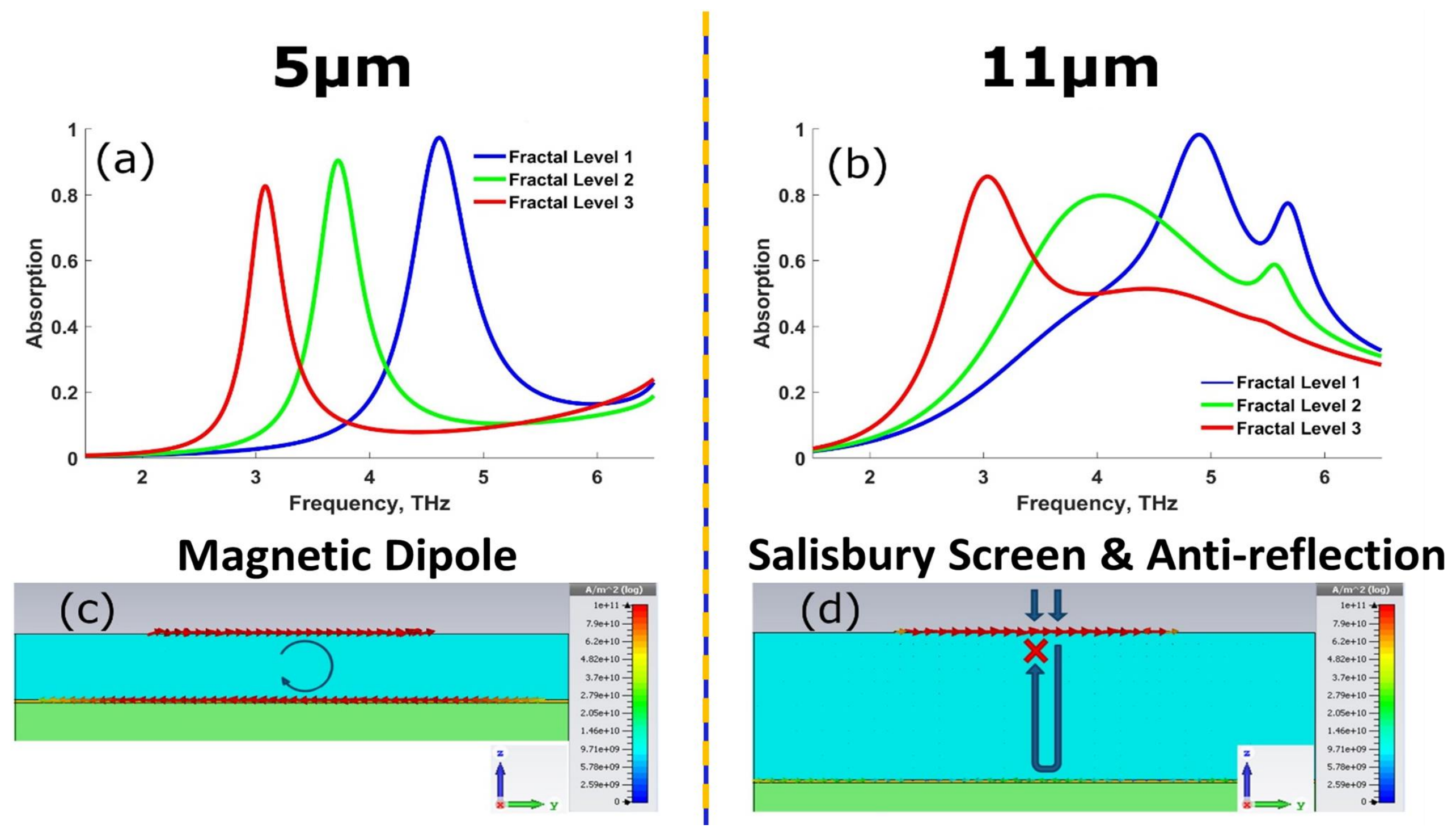


Fig. 3 – (a) Narrowband absorption for fractal levels 1-3. **(b)** broadband responses for fractal levels 1-3. **(c)** 2D current density plot, showing typical magnetic dipole formation from coupled resonances. **(d)** novel absorption using SS and AR responses – current only present on fractal crosses.

Broadband Supercell Design

Owing to the property of frequency red-shift with increasing fractal order, we combined all three fractals into a **supercell** as shown in **Fig. 4**. Also, combined with the broadband nature of the 11 μm polyimide (PI) arrangement, it should lend itself to ultra-broadband operation.

Simulations were carried out at normal incidence for both thin (5 μm) and thick (11 μm) PI thicknesses (shown below, **Fig. 5**). We see that for 5 μm simulations, the absorption is very poor, whilst for 11 μm simulations the absorption is very high and broadband. We owe the poor performance for 5 μm to the extending ground-plane currents and out-of-phase coupling to neighbouring currents. For 11 μm, no ground-plane currents exist.

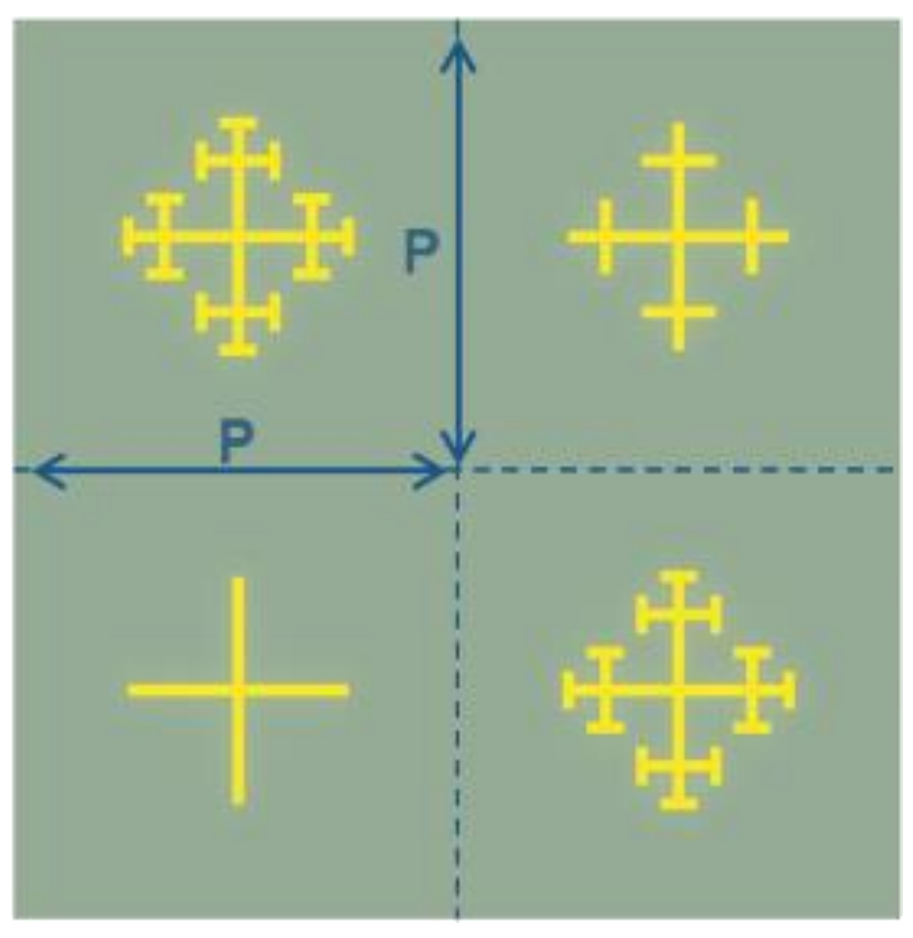


Fig. 4 – Supercell design, combining Fractal Cross Levels 1 to 3.

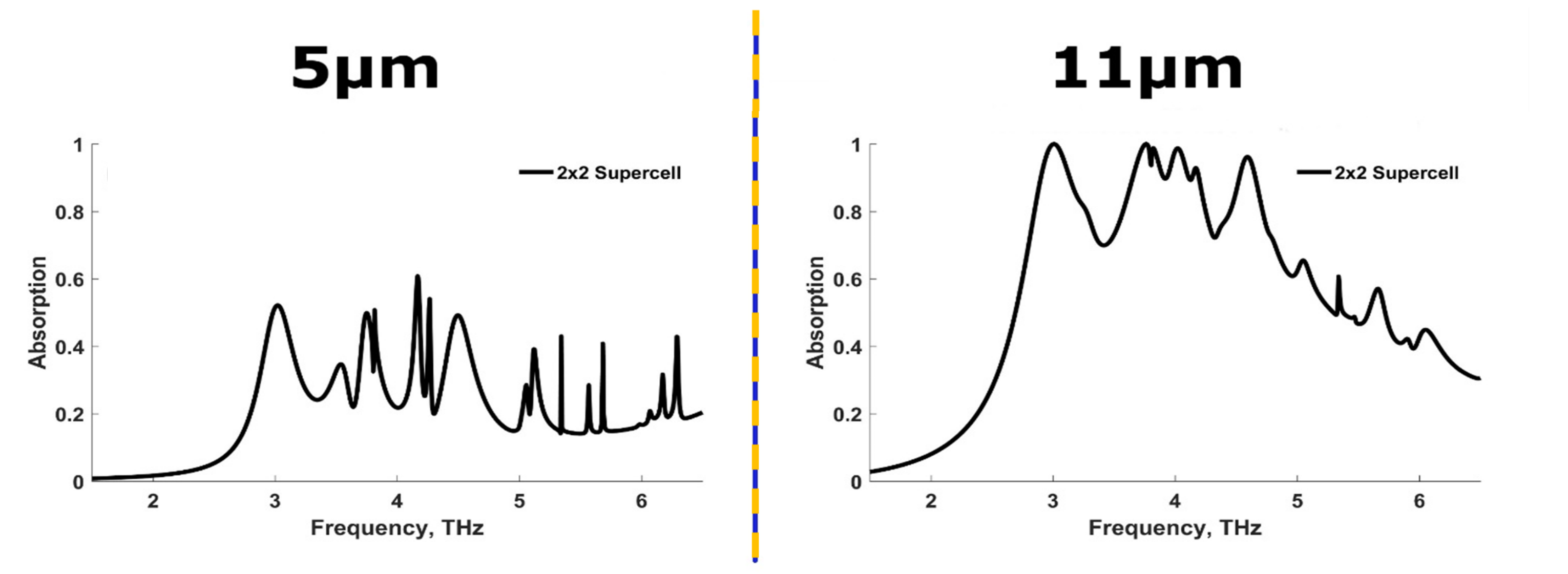


Fig. 5 – Simulated supercell spectra for both **(Left)** 5 μm and **(Right)** 11 μm thick polyimide samples.

FTIR and Simulation Spectra

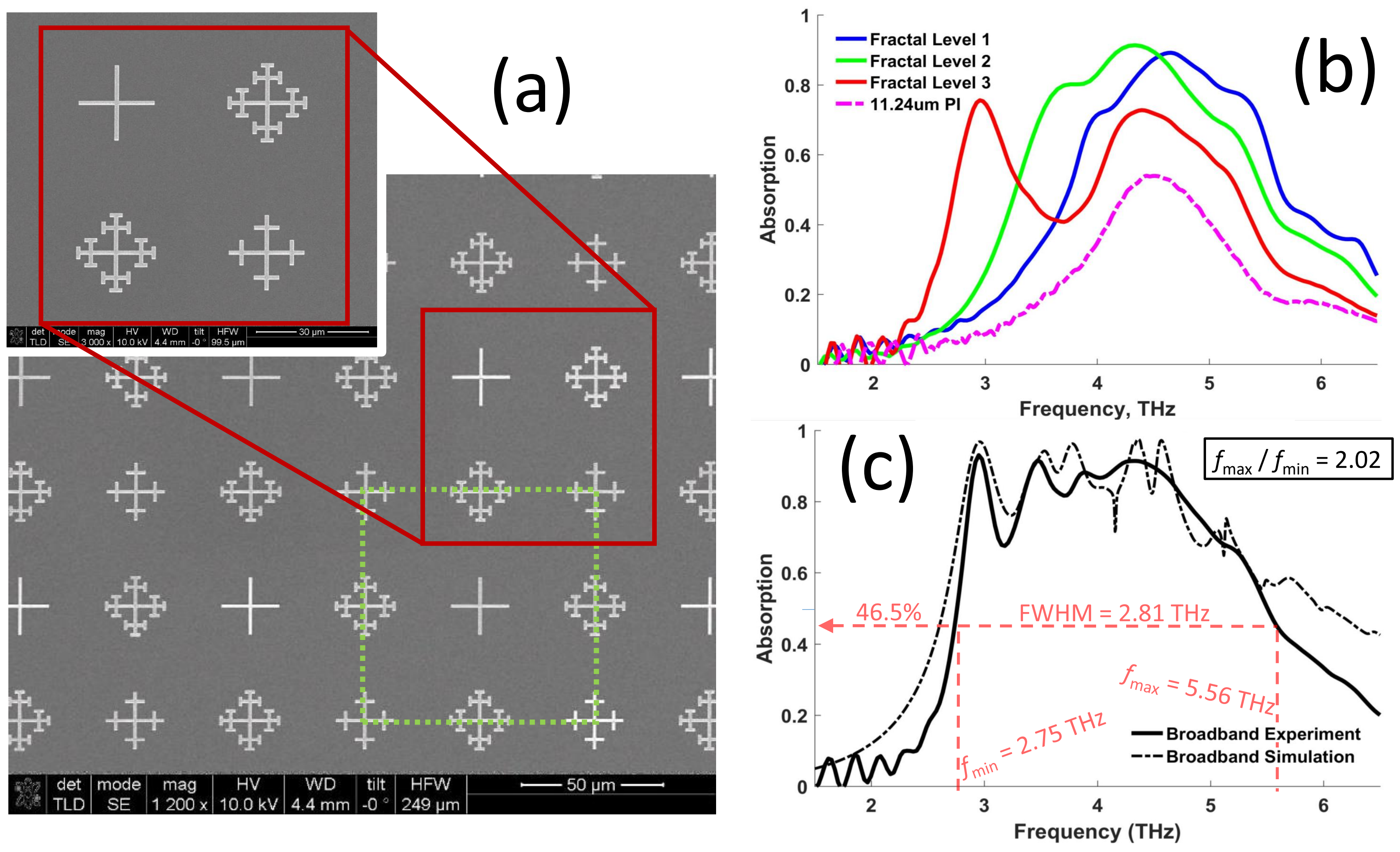
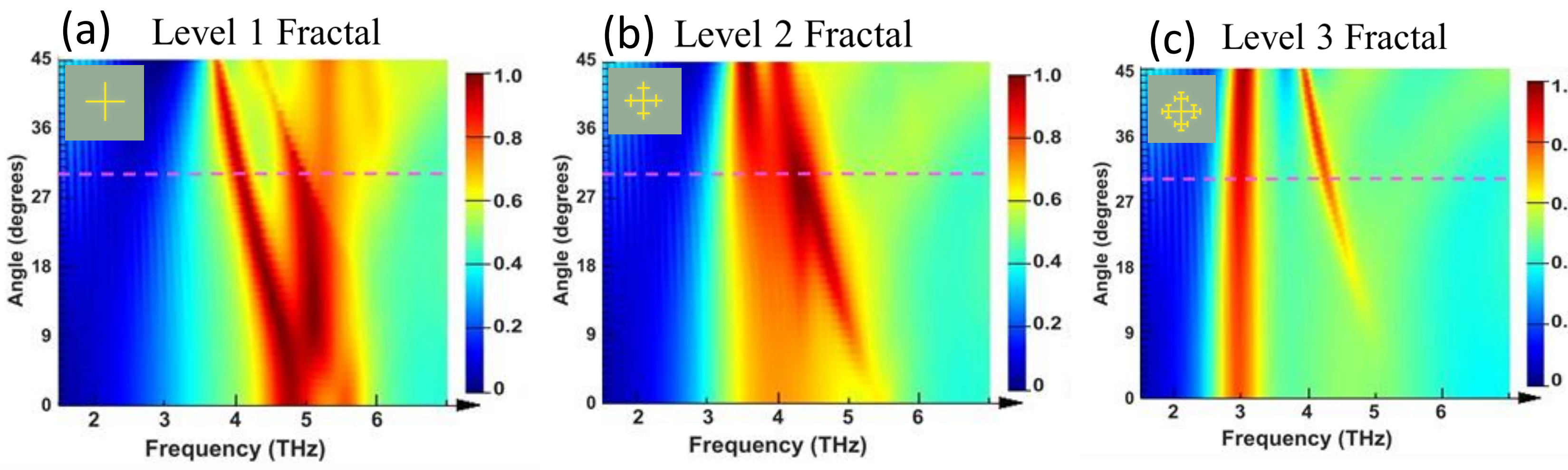


Fig. 6 – (Left) SEM images. The green box signifies rotational & mirror symmetry, implying polarization insensitivity. **(Right)** Experimental FTIR spectra of **(top)** single-pattern and **(bottom)** supercell designs.

Four designs (fractal levels 1, 2, 3, supercell) were fabricated by evaporating gold (100 nm) onto silicon wafers, spin-coating polyimide (11.24 μm), e-beam lithography of patterns, and standard lift-off process using gold (100 nm). Scanning electron microscope (SEM) images are shown in **Fig. 6a**.

Samples were characterized using a Fourier Transform Infra-Red (FTIR) spectrometer (Bruker IFS 66v/S) at 30° incidence angle (limitation of FTIR), shown above in **Fig. 6b, c**. Spectra coincide with the **PI response** at ~**4.5 THz** (**AR response**), whilst Fractal level 3 (red curve) has an additional peak at ~3 THz (SS response), thus confirming our hypothesis. The supercell design (Fig. 6c) is indeed very broadband. A **peak absorption of 93%** is obtained. The **FWHM** (43.5%) **bandwidth** corresponds to an **optical octave** in span. Matching simulation in Fig. 6c was obtained using a new PI refractive index of n = 1.71 + 0.08i.



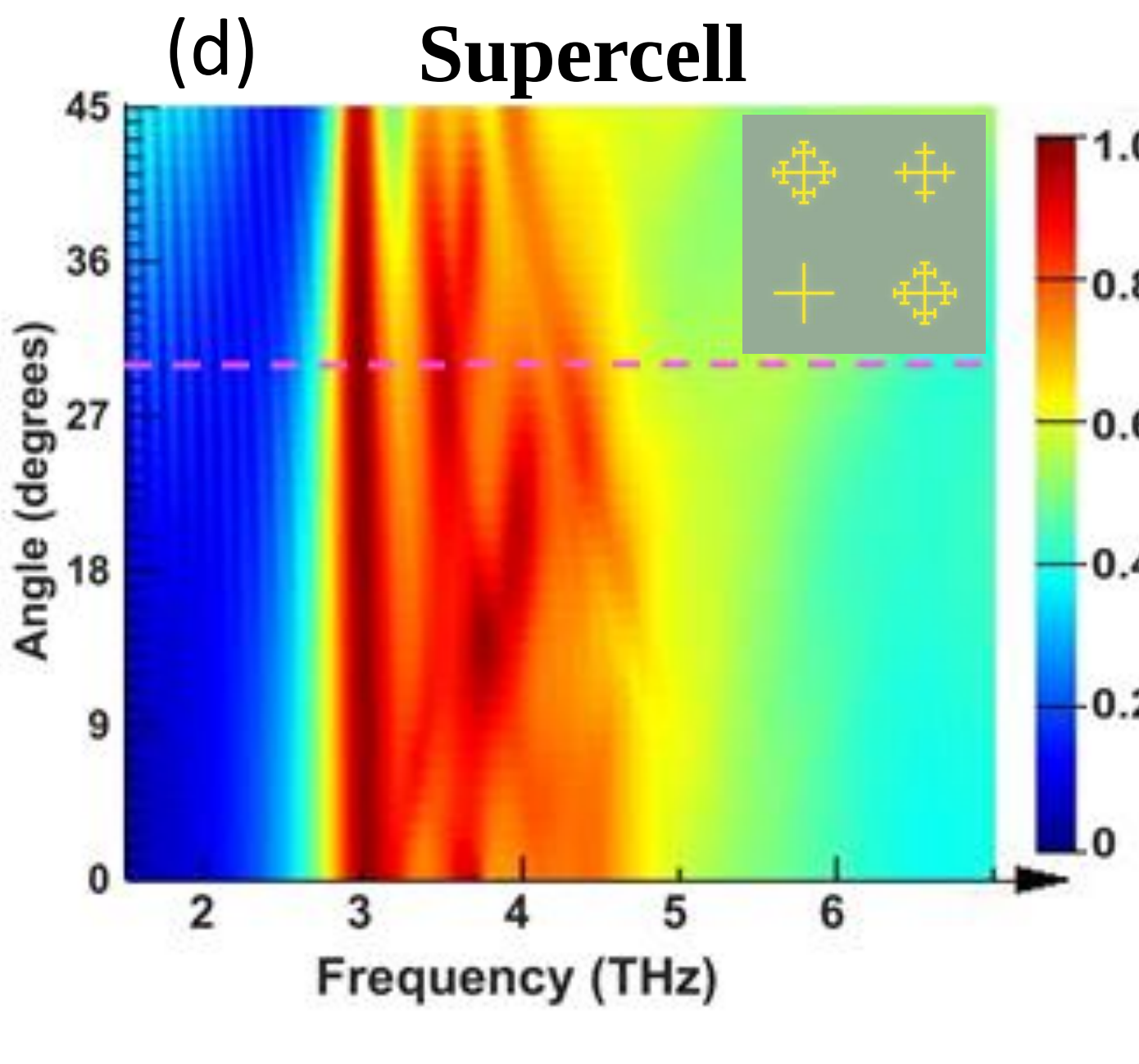


Fig. 7 – Absorption frequency contour plots with varying incident angle for **(Top Row)** fractal levels 1 to 3 and **(Right)** supercell designs, for 11.24 μm polyimide thickness.

Due to the experiment at 30°, we performed simulations of the **angle dependency** of the designs (**Fig. 7**). A **red-shift** of the **AR response** is seen with **increasing angle** (especially Fig. 7c) owing to the **longer path-length** of light.

The supercell design seems very robust and tolerant to the incident angle, making the design highly suitable for commercial applications.

Conclusion and Future Work

We have shown the design, simulation, and experimental realization of an octave-spanning metasurface broadband absorber, which uses fractals to broaden the response. Fractals are very compact compared to standard crosses, for the same frequency, and so are of great use for commercial applications where compactness is important. One highly realizable device is a THz blackbody absorber, where combining our device with bolometers will prove very useful for sensing applications. We believe that the bandwidth of this work can be improved even further by careful increasing of fractal levels, and by incorporating multi-layer designs.

References

[1] J. Grant, Y. Ma, S. Saha *et al.*, *Optics Letters*, **36**, 3476–3478 (2011)
[2] Y. Ma, Q. Chen, J. Grant *et al.*, *Optics Letters*, **36**, 945-947 (2011)
[3] M. Kenney, J. Grant, Y. Shah *et al.*, *ACS Photonics*, In press (2017)

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