Broadband 1-3 Piezoelectric Composite Transducer Design using Sierpinski Gasket Fractal Geometry

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Abstract—Wider operational bandwidth is an important requirement of an ultrasound transducer across many applications. In nature, it can be observed that several hearing organs possess a broad operating bandwidth by having a varying length scales structure. Moreover, conventional 1-3 piezoelectric composite transducers have been widely recognized for their wider bandwidth over their piezoelectric ceramic counterparts. In this paper, a novel 1-3 piezoelectric composite design using a fractal geometry, known as the Sierpinski Gasket (SG), is proposed in order to explore the potential of further extending the operational bandwidth and sensitivity of the transducer. Two equivalent 1-3 piezocomposite designs are compared to this end, one with a conventional periodic parallelepiped shaped pillar structure and one with the SG fractal geometry, both theoretically, using a finite element (FE) analysis package, and experimentally. The transmit voltage response and open circuit voltage response are used to illustrate bandwidth improvement from the fractal composite design. Following the simulation results, a 580 kHz single element transducer, utilizing the proposed SG fractal microstructure, is fabricated using a pillar placement methodology. The performance of the prototyped device is characterized and compared with a conventional 1-3 composite design, as well as with a commercial ultrasound transducer. In the one-way transmission mode, a bandwidth improvement of 27.2 % and sensitivity enhancement of 3.8 dB can be found with the SG fractal design compared to an equivalent conventional composite design and up 105.1 % bandwidth improvement when compared to the commercial transducer. In the one-way reception mode, the bandwidth improvement for the SG fractal design is 2.5 % and 32.9 % when compared to the conventional and commercial transducers, respectively.

I. INTRODUCTION

The concept of a ‘piezoelectric composite’ ultrasound transducer is well-established [1], [2], [3]; such ultrasound transducers comprise an active piezoelectric phase and a passive, typically polymer phase. Such piezoelectric composite configurations, when designed correctly, can attain high sensitivity whilst being well matched to a low acoustic impedance load [4][5]. Piezoelectric composite ultrasound transducers with a wide operational bandwidth are preferred in many applications, such as underwater sonar, non-destructive testing (NDT) and biomedical imaging [6] [7] [8] [9]. A broadband transducer can offer better spatial resolution and therefore better imaging performance. Wider operational bandwidth at the transducer can offer advantages in the signal processing chain of contemporary imaging systems. Frequency diverse signal processing techniques such as split spectrum processing [10] benefit form wider transducers bandwidth when applied to speckle reduction [11] and contrast enhancement [7].

There are many different techniques which have been developed in order to achieve the enhancement of the operational bandwidth for an ultrasound transducer. To summarize, there are three popular methods to achieve this goal:

a) Improve the piezoelectric material properties,
b) Modify the matching/backing design,
c) Optimize the composite structure, including the filler material properties.

For enhancing the piezoelectric material properties, Yamada et al. [12] proposed a method of designing a broadband ultrasound transducer by giving the piezoelectric plate a temperature gradient in its thickness direction via a controlled temperature based depoling procedure, resulting in a graded piezoelectric constant (e33) [12]. Wong et al. [13] designed a high frequency phased array ultrasound transducer with a PMN-PT single crystal material and when compared with other piezoceramic designs, this single crystal material exhibited a wider operational bandwidth. For increasing the transducer bandwidth with an optimized matching design, Hossack and Auld [14] reported a novel transducer design with an active piezoelectric matching layer. Moreover, many researchers improved the bandwidth of the ultrasound transducer by optimizing the structure of the composite design. Harvey et al. designed a random composite transducer with piezoelectric fibers to improve the device bandwidth [15]. Ramadas et al.
developed a wideband annular piezoelectric transducer by combining four concentric piezoelectric composite annuli each exhibiting a different fundamental thickness mode resonance [16]. Similarly, Banks et al. [17] proposed two novel piezoelectric composite transducer designs to enhance the operating frequency of the device for air-coupled non-destructive evaluation, the dual thickness piezocomposite and conical piezocomposite design. Both designs achieved a bandwidth enhancement successfully by having a varied thickness dimension to introduce multiple thickness mode resonances into one piezocomposite design. Espinosa et al. [18] developed a dual frequency 1-3 piezocomposite transducer for the purpose of performing the harmonic imaging in the field of medical ultrasound. This 1-3 piezocomposite transducer design was comprised of ceramic pillars in three different shapes. By carefully choosing the thickness and different lateral dimensions of the pillars in the piezocomposite plate, two main resonance modes, $f$ and $2f$, can be obtained, which was used as the transmission mode frequency and the reception mode frequency, respectively. Guo et al. presented a partial piezoelectric composite device design, where the thickness dimension piezoelectric plate was only partially diced and subsequently filled. The device in effect comprised a monolithic piezoelectric device combined with a piezoelectric composite. By doing so, a device exhibiting graded piezoelectric properties in the thickness direction was obtained that offered improved bandwidth at the fundamental thickness mode [19]. Yang et al. developed a pseudo-random composite transducer by dicing the ceramic plate with two sets of cross cuts at different angles relative to the horizontal [20]. The pulse-echo response bandwidth of this pseudo-random composite was increased by 13% when compared to a standard 1-3 composite design. These techniques support the concept that the bandwidth of an ultrasound transducer can be extended using any one of the three popular approaches described earlier.

In naturally occurring auditory systems, it is common to observe hearing organs comprised of a number of different length scales. Such hearing organs exhibit extended operating bandwidth, examples include insects such as the bushcricket [21], [22], [23]. In common with all resonating systems, the resonance frequency of a piezoceramic resonator depends on its length scale. Therefore, having a high level of geometric complexity with a range of length results in a range of resonance frequencies, and therefore a broadening of the overall operational frequency range.

In this paper, a self-similar fractal geometry known as the Sierpinski Gasket (SG), shown in the Fig. 1, will be adopted as the structure of a piezocomposite design in order to explore improvements in the bandwidth of the 1-3 composite configuration transducer. This concept of engineered transducers comprised of multiple length scales has been developed mathematically [24], [25], [26] and these analytical models indicate that by having elements with varying length scales in the piezoelectric transducer design, the device may possess a wider operational bandwidth or a higher sensitivity compared to a conventional device. In addition, it has been shown that devices comprising of triangular pillars, resulting in an absence of parallel faces between elements in a composite design, reduce the inter-pillar resonant activity in the lateral dimension [27]. Therefore, the thickness coupling efficiency can be increased, leading to a potential improvement in the device sensitivity.

Fig. 1: The first four fractal generation levels of the SG Fractal Geometry

II. SIERPINSKI GASKET GEOMETRY

The primary shape of the SG fractal geometry is an equilateral triangle, where the fractal configuration at higher generation levels can be achieved by subdividing the entire equilateral triangular recursively into several similar equilateral subtriangles. The lateral width of the subtriangle at the $k_{th}$ fractal generation level, $L_k$, can be calculated in terms of the total lateral length of the entire fractal geometry, L, via

$$L_k = \frac{L}{2^k}.$$  

The finite element (FE) analysis package, PZFlex (OnScale Inc, Cupertino, CA), will be used to analyze the SG design, specifically considering the transmission and reception response of a SG fractal composite and an equivalent standard composite design to provide the proof of concept for this broadband fractal composite design approach. Then, the first prototype incorporating this SG fractal composite approach will be manufactured using a pillar placement methodology.

The performance of this SG fractal device in one-way transmission mode, one-way reception mode and two-way pulse-echo mode will be tested experimentally and compared with the conventional composite device and an unfocused commercial ultrasound device. It will be shown, theoretically and experimentally, that an encouraging bandwidth improvement can be achieved by implementing the SG fractal geometry compared to the conventional composite design which has a regular periodic structure.

III. MODELING

A. SG Fractal Composite Transmission Performance at Different Fractal Generation Levels

First of all, how the fractal generation level of a SG fractal geometry configuration would influence the transmit performance of the piezocomposite device was investigated. In order to explore the problem space, several 3D FE models of the unmatched SG fractal composite microstructure from fractal generation Level III to Level VI and their corresponding equivalent conventional 1-3 composite designs were simulated using PZFlex with water load. The active and passive phase
material are determined to be PZT-5H ceramic and hardset polymer, respectively. For each SG fractal model, the lateral length of the smallest triangular was kept as 1 mm. In terms of each conventional 1-3 composite plate model, the pillar width was maintained the same as 1 mm, whilst the ceramic volume fraction (VF) was varied in order to keep it the same as the SG fractal composite design at different fractal generation levels, aiming to provide a fair comparison between the two designs in terms of the sensitivity level. The ceramic volume fraction of the SG fractal generation Level III to Level VI composites and their equivalent conventional 1-3 composites are 57.8 %, 68.4 %, 76.3 % and 82.2 %, respectively. To determine the composite thickness for all of these models, the maximum pillar aspect ratio (MPAR) concept reported by Hayward and Bennett [3] for 1-3 configurations was utilized to ensure a high electromechanical coupling efficiency in the thickness resonance mode for ceramic volume fractions above 50%. Accordingly, in the 1-3 composite case, the MPAR should be limited to 0.39, resulting in a 2.6 mm layer thickness and this thickness has been used in each model for a fair comparison between SG fractal composite and conventional 1-3 composite.

The transmit voltage response (TVR) spectrum of these SG composites from fractal generation Level III to Level VI were simulated and compared to the equivalent conventional composite designs – for each of case the results are shown in Fig. 2 and Table I.

![Fig. 2: Simulated TVR of the conventional and the SG composite (Level III to Level VI)](image)

<table>
<thead>
<tr>
<th>Level No.</th>
<th>VF</th>
<th>SG Composite</th>
<th>Conventional Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level III</td>
<td>57.8 %</td>
<td>Bandwidth: 158.5 dB Sensitivity: 47.1 %</td>
<td>Bandwidth: 35.2 % Sensitivity: 161.8 dB</td>
</tr>
<tr>
<td>Level IV</td>
<td>68.4 %</td>
<td>Bandwidth: 166.5 dB Sensitivity: 71.4 %</td>
<td>Bandwidth: 40.1 % Sensitivity: 165.0 dB</td>
</tr>
<tr>
<td>Level V</td>
<td>76.3 %</td>
<td>Bandwidth: 168.4 dB Sensitivity: 82.8 %</td>
<td>Bandwidth: 62.7 % Sensitivity: 167.6 dB</td>
</tr>
<tr>
<td>Level VI</td>
<td>82.2 %</td>
<td>Bandwidth: 179.6 dB Sensitivity: 46.5 %</td>
<td>Bandwidth: 45.0 % Sensitivity: 174.2 dB</td>
</tr>
</tbody>
</table>

It can be seen that the SG composite at the third level behaved approximately the same as the conventional composite. However, as the generation level increases beyond three, the SG composite starts to show improved fractional bandwidth when compared to the conventional composite design. For example, at generation level IV, the -6 dB bandwidth of the unmatched SG fractal composite plate is 71.4 % compared to 40.1 % for the conventional composite plate. Considering the difficulties of the manufacturing process, the Level IV SG fractal composite was considered as a good initial choice for studying and manufacture in this work.

The effective electromechanical coupling coefficient, \( k_t \), is a well understood figure of merit for transducer performance and can be calculated using Eq. (2), where it is expressed as a function of separation of the resonant frequency, \( f_r \), and anti-resonance, \( f_a \), of the device via:

\[
k_t = \sqrt{\frac{\pi^2 \times f_r}{2 \times f_a} (\frac{\pi}{2 \times f_a})} \tag{2}
\]

The \( k_t \) values of the four SG fractal composites and their equivalent conventional 1-3 composites were determined using the FE derived impedance spectra, these data are plotted in Fig. 3. In order to make further comparison, the \( k_t \) of the conventional 1-3 composites across the ceramic volume fraction range was determined using the Smith-Auld model [28], again these data are plotted in Fig. 3, where it can be seen that the \( k_t \) simulated with the Smith-Auld model matches with the results achieved by the FE model for the conventional composites. In addition, the general behavior of 1-3 connectivity composites can be observed where a maximum in \( k_t \) is typically observed in the 50-65 % ceramic volume fraction range. The motivation in the design of the 1-3 composite is to attain a maximal \( k_t \), where in theory this is limited by the \( k_{33} \) of the piezoelectric material.

Considering the data for the SG composite devices shown in Fig. 3, \( k_t \) is observed to exhibit different behavior to that of the conventional 1-3 composite, attaining a maximum at a higher ceramic volume fraction than would typically be observed in a 1-3 connectivity composite. Furthermore, it can be clearly seen from Fig. 3 that the \( k_t \) of the SG composites is always higher than the equivalent conventional 1-3 composites across all the ceramic volume fractions under this study. Moreover, \( k_t \) of the Level V SG composite is beyond the \( k_{33} \) of PZT-5H ceramic, typically 0.70. By considering Eq. (2), it can be seen that the frequency separation of the resonance and anti-resonance governs the magnitude of \( k_t \). In the SG composite device, there are number of coupled modes that act in concert at the thickness mode, thereby extending the frequency separation of the two resonances resulting in a \( k_t \) for the device beyond the theoretical maximum.

In subsequent section of this paper, the SG device at Level IV will undergo further analysis and its performance will be compared to a conventional 1-3 composite of the same volume fraction. While it is recognized that a ceramic volume fraction of 68.4 % is not the optimized choice for the conventional 1-3
composite in imaging applications, although the device still gives a reasonable performance before the $k_t$ further decreases with increased ceramic volume fraction.

![Simulated $k_t$ for SG and conventional 1-3 composite with different ceramic volume fraction](image)

Fig. 3: Simulated $k_t$ for SG and conventional 1-3 composite with different ceramic volume fraction

**B. SG Fractal Composite at Fractal Generation Level IV**

The SG fractal of generation level IV was identified for further investigation using FE modelling suit. Fig. 4(a) illustrates the SG fractal composite design, where the active phase of this SG composite is comprised of equilateral triangular ceramic pillars with different lateral length scales. Fig. 4(b) shows an equivalent conventional parallelepiped 1-3 composite design. Consistency is maintained between the two composite designs in five aspects by ensuring each device has the same fundamental design parameters.

1) PZT5H ceramic and hardset polymer are chosen to be the active and passive phase, respectively.

2) The lateral length of the smallest triangular pillar at the fourth generation level in the SG composite, $L_4$ as defined in Eq. (1), is chosen to be 1 mm and this same pillar width value is assigned to the conventional composite design. The kerf width of the conventional composite is 0.2 mm. The thickness of both devices is set to be 2.6 mm for the purpose of minimizing the negative effect caused by the pillar vibrating in the lateral direction.

3) Ceramic volume fraction of both composite designs are both 68.4% because of the fixed configuration layout of the SG fractal geometry.

4) The active aperture area for both composite designs are approximately the same, which is 111 mm$^2$.

5) The same matching layer arrangement will be incorporated into both composite designs.

![3D FE composite model, (a) Level IV SG fractal piezocomposite; (b) conventional 1-3 piezocomposite](image)

Fig. 4: 3D FE composite model, (a) Level IV SG fractal piezocomposite; (b) conventional 1-3 piezocomposite (Black: Ceramic Pillar; Gray: Polymer Filler)

1) **Electrical Impedance Profile**

In order to explore the resonance behavior of the SG fractal composite in details, the electrical impedance magnitude spectra of the Level IV SG composite and conventional composite are simulated in water load without matching layer. It can be seen in Fig. 5 that the SG fractal composite and the conventional composite exhibit electrical impedance minima at 580 kHz and 575 kHz, respectively. Moreover, a multi-modal characteristic is exhibited in the SG fractal design due to its varying pillar length scale.

![FE derived electrical impedance magnitude spectrum of the SG and the conventional composite](image)

Fig. 5: FE derived electrical impedance magnitude spectrum of the SG and the conventional composite

The resonant and anti-resonant frequencies of each composites were used to calculate the effective electromechanical coupling coefficient, $k_t$. Compared to the conventional design, the SG fractal composite achieved a larger value of $k_t$, which is 0.72 against 0.65 for the conventional composite. Therefore, a better energy conversion and improved bandwidth may be realized by the SG fractal design. Three modes are found in the SG fractal design at 580.0 kHz, 705.4 kHz and 790.0 kHz. At each frequency, the displacement mode shape in thickness direction was investigated and shown in the Fig. 6.

![Displacement mode shape](image)

Fig. 6: Displacement mode shape in thickness direction.
The surface dilation quality factor $Q_{dit}$, which is used for describing the uniformity of the surface displacement, was calculated in thickness direction using Eq. (3) for each of the 3 resonance frequencies shown in Fig. 6 [29].

$$Q_{dit} = \frac{D_{ave}(\omega_i)}{D_{max}(\omega_i)}$$

where $\omega_i$ is the radial frequency of the $i$th resonance mode and $D_{ave}$ and $D_{max}$ is the surface average and maximum displacement, respectively. The calculated result is presented in Table II.

Table II: Calculated $Q_{dit}$ at each resonance frequencies

<table>
<thead>
<tr>
<th>Resonance Frequencies</th>
<th>580.0 kHz</th>
<th>705.4 kHz</th>
<th>790.0 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{dit}$</td>
<td>0.72</td>
<td>0.21</td>
<td>0.20</td>
</tr>
</tbody>
</table>

From the Fig. 6 and Table II, the strong thickness mode behavior in the pillars associated with the 2nd, 3rd and 4th generation levels at 580kHz has produced the highest $Q_{dit}$, which is 0.72. For the resonances at 705.4 kHz and 790 kHz, the lateral resonances from the 1st and 2nd generation levels dominate the vibrational response and the corresponding $Q_{dit}$ figures are 0.21 and 0.20, respectively. These dilation quality factors are lower than a conventional 1-3 composite device, which is 0.95, due to the antiphase resonance behavior present in the triangular pillars with large pillar aspect ratio in generation level I and II, although the main thickness mode resonance vibrational response for the SG device is still considered to be sufficiently high for acceptable operational performance. It is worth noting that the design premise of the fractal geometry composite is to couple different resonance modes and hence, the design philosophy is not directly comparable to the well-known conventional 1-3 composite theory. The operational behavior of the SG composite will now be evaluated through both simulation and experimentation.

2) Pulse-Echo, Transmission & Reception Response Modeling

In order to compare the performance of the two piezoelectric composite designs described in the Section III.B, a FE model was constructed to simulate the operation of both devices when matched to a water load via a dual matching layer scheme. For the purpose of maximizing the output signal strength and to avoid obscuring the distinct resonances of the SG fractal structure, the backing layer was not incorporated into the transducer design in this paper. A schematic of the transducer arrangement is depicted in Fig. 7. The performance of the two devices, each incorporating a dual matching layer, was then assessed by considering the transmitting voltage response (TVR) and the open circuit voltage response (OCV) as determined in the FE model from the simulations.

For each matching layer, the acoustic impedance, $Z_1$ and $Z_2$, and thickness, $t_1$ and $t_2$, can be calculated using the acoustic impedance of the load and transducer itself, $Z_L$ and $Z_T$, through the transfer matrix method [30], [31], where $Z_L$ is 1.5 MRayl for water and $Z_T$ is calculated using the Smith-Auld approach [28] according to the ceramic volume fraction of the composite and material properties. As both composites have the same ceramic volume fraction and active/passive materials, $Z_T$ was calculated as 19.9 MRayl for both composites.

The ideal acoustic impedance of each matching layer, $Z_1$ and $Z_2$, can be calculated using Eqs. (4) and (5) [32].

$$Z_1 = Z_T^{\frac{4}{7}} \times Z_L^{\frac{6}{7}}$$

$$Z_2 = Z_T^{\frac{4}{7}} \times Z_L^{\frac{3}{7}}$$

The calculated values for $Z_1$ and $Z_2$ for a theoretically optimal matching layer are 2.2 MRayl and 6.6 MRayl, respectively. Consequently, the CY221/HY956EN medium set polymer (Robnor Resin Ltd, UK) was chosen as the material of the Matching Layer I, whose acoustic impedance is 2.68 MRayl. The RX771C(NC)/CY1300 hardset polymer (Robnor Resin Ltd, UK) filled with $\mu$m alumina powder using 70 % weight fraction was determined to be the material of the Matching Layer II, which has the acoustic impedance of 6.96 MRayl [33]. Once the impedance of each layer is selected, layer thickness can be determined using Eqs. (6), (7) and (8) [30].

$$\tan \theta_1 = \frac{4}{\pi} \left[ \frac{Z_1 - Z_2}{Z_2 - Z_1} \right]^{\frac{1}{2}}$$

$$\tan \theta_2 = \left[ \frac{\alpha(Z_1 - Z_2)}{Z_2 - Z_1} \right]^{\frac{1}{2}}$$

where $\alpha = 4.98$, $\beta = 1.60$ (as calculated from reference [30]) and the $\theta_n$ is the phase shift in each matching layer as determined by the wavelength $\lambda_n$ and the thickness $t_n$ of each matching layer, which is given by

$$\theta_n = 2\pi \frac{t_n}{\lambda_n}.$$
the second matching layer.

The predicted TVR and OCV are obtained using Eqs. (9) and (10), where the resulting spectra are shown in Fig. 8 and Fig. 9, respectively. The simulated pulse-echo responses for both devices are shown in Fig. 10.

\[
TVR = 20 \log(\frac{\text{Pressure/V}_{\text{in}}}{\text{Pressure/V}_{\text{in}}}), \tag{9}
\]

\[
OCV = 20 \log(\frac{\text{V}_{\text{out}}/\text{V}_{\text{in}}}{(\text{Pressure/V}_{\text{in}}))}. \tag{10}
\]

As seen in Table III, by using the SG fractal geometry as the structure of a piezoelectric composite transducer design, both operational bandwidth and sensitivity level are enhanced. In transmission mode, a 8.8 % bandwidth improvement and a 4.2 dB sensitivity increment were achieved. In reception mode, although the peak of the OCV of the SG fractal device and conventional device are approximately the same, the bandwidth was enhanced by 5.4 % when compared to the conventional device. Lastly, in the two-way pulse-echo mode, the bandwidth and signal strength improvement are 12.1 % and 10.7 % for the SG fractal design, when compared to the conventional composite design.

3) Beam Profile Modeling

The beam profile of the SG fractal and the conventional composite at their rotating center plane, indicated with the red dash line in Fig. 11, was simulated using Huygens-Fresnel principle at their resonant frequencies, which is 580 kHz and 575 kHz, respectively.

It can be seen from Fig. 11 that the SG fractal device has a lower side lobe level and tighter focal zone when compared to the conventional composite design. The near-field point of the SG fractal and the conventional composite is 9.9 mm and 15.6 mm, respectively according to their different geometry.

<table>
<thead>
<tr>
<th>Table III: Simulated pulse-echo, transmission and reception results</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td><strong>Transmission Bandwidth (%)</strong></td>
</tr>
<tr>
<td>SG Composite: 76.9 %</td>
</tr>
<tr>
<td>Conventional Composite: 70.8 %</td>
</tr>
<tr>
<td><strong>TVR Peak (dB)</strong></td>
</tr>
<tr>
<td>SG Composite: 184.1 dB</td>
</tr>
<tr>
<td>Conventional Composite: 179.9 dB</td>
</tr>
<tr>
<td><strong>Reception Bandwidth (%)</strong></td>
</tr>
<tr>
<td>SG Composite: 85.2 %</td>
</tr>
<tr>
<td>Conventional Composite: 80.8 %</td>
</tr>
<tr>
<td><strong>OCV Peak (dB)</strong></td>
</tr>
<tr>
<td>SG Composite: -168.5 dB</td>
</tr>
<tr>
<td>Conventional Composite: -168.6 dB</td>
</tr>
<tr>
<td><strong>Pulse-Echo Bandwidth (%)</strong></td>
</tr>
<tr>
<td>SG Composite: 66.7 %</td>
</tr>
<tr>
<td>Conventional Composite: 59.5 %</td>
</tr>
<tr>
<td><strong>Pulse-Echo Peak-to-Peak Voltage (mV)</strong></td>
</tr>
<tr>
<td>SG Composite: 498.9 mV</td>
</tr>
<tr>
<td>Conventional Composite: 450.8 mV</td>
</tr>
</tbody>
</table>

Fig. 8: Simulated TVR spectrum of the SG and the conventional composite ultrasonic transducers

Fig. 9: Simulated OCV spectrum of the SG and the conventional composite ultrasonic transducers

Fig. 10: Simulated pulse-echo responses of the SG and the conventional composite ultrasonic transducers

The peak gain and -6 dB operational bandwidth for both devices in one-way transmission and reception mode and two-way pulse-echo model are shown in Table III.
IV. FRACTAL COMPOSITE TRANSDUCER FABRICATION

Based on the positive simulation results in the previous sections, an initial prototype SG fractal composite transducer at fractal generation level IV was manufactured. The manufacturing process of this fractal composite involved a 3D printing technique to produce a mould, followed by a pillar placement methodology, which is described in 4 steps.

1) The equilateral triangular ceramic pillars at different fractal generation levels were prepared by dicing (MicroACE Series 3 Dicing Machine, Loadpoint, UK) commercial PZT-5H ceramic plates (Meggitt A/S, Kvistgard, Denmark) into appropriate geometries, as shown in Fig. 12 (a). The lateral dimension of these equilateral triangular ceramic pillars from level I to level IV is 8 mm, 4 mm, 2 mm and 1 mm respectively.

2) 3D printer (Pico Plus 27, ASIGA, USA) was used to manufacture a mould to represent the negative of the SG fractal geometry, which is shown in Fig. 12 (b), for the function of holding the ceramic pills in position.

3) The ceramic pillars were placed in the mould, shown in Fig. 12 (c) and filled with RX771C(NC)/CY1300 hardset epoxy polymer (Robnor Resin Ltd, UK), as shown Fig. 12 (d).

4) Once the polymer filler was fully cured, the mould was machined off and the composite plate was lapped down to the desired thickness, 2.6 mm. The prototype of this SG fractal composite is shown in Fig. 12 (e) and is the first manufactured piezoelectric device based on fractal theory.

![Fig. 12: SG fractal composite fabrication process: (a) individual cut ceramic pillars with different sizes; (b) 3D printed mould; (c) ceramic pillars are placed in the mould; (d) the mould is filled with polymer; (e) the surplus mould is machined off.](image)

An equivalent conventional parallelepiped 1-3 composite was also fabricated using the traditional dice-and-fill technique, in order to compare performance. For each device a dual matching layer was employed, the design of which is described in Section III.B.2). Finally, each device was secured into a water proof housing. Fig. 13 shows a photograph of the complete SG fractal piezoelectric composite transducer (Left) and an equivalent conventional composite (Right) together with a £1 coin (Middle) which has a diameter of 25 mm.

![Fig. 13: SG fractal (Left) & conventional composite (Right) ultrasonic transducer](image)

V. EXPERIMENTAL VALIDATION

The performance of the manufactured SG fractal composite transducer was characterized experimentally in three different modes: one-way transmission, one-way reception and two-way pulse-echo. The measured TVR, OCV and the pulse-echo response of the SG fractal composite device are compared with the equivalent conventional composite design and an unfocused commercial ultrasound transducer (A301 S, Panametrics, USA). The specifications of three devices are stated in the Table IV below.

<table>
<thead>
<tr>
<th></th>
<th>Pulse-Echo Centre Frequency</th>
<th>Active Aperture Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG Fractal Device</td>
<td>596 kHz</td>
<td>131.9 mm²</td>
</tr>
<tr>
<td>Conventional Device</td>
<td>587 kHz</td>
<td>123.2 mm²</td>
</tr>
<tr>
<td>Panametrics Commercial Device</td>
<td>547 kHz</td>
<td>615.7 mm²</td>
</tr>
</tbody>
</table>

It should be noticed that the commercial device has a much larger active area compared with the two fabricated devices: this significant active area difference will be taken into account in the experimental results comparison between these three devices.

A. IMPEDANCE RESPONSE OF FABRICATED DEVICES

The electrical impedance responses of the fabricated devices with matching layers casted were measured in air and they correlate well with the simulation results, as shown in Fig. 14. The $k_e$ were measured as 0.54 and 0.50 for the SG fractal and conventional composite, respectively and the relative dielectric constants, $\varepsilon_r$ of both devices using the constant strain condition are calculated as 706 and 986 for the SG and conventional composite, respectively.

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This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TUFFC.2018.2874384, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control

B. Transmission Response Measurement

For characterizing the performance of the devices in transmission mode, the TVR of these three devices was measured experimentally. A function generator (33210A, KEYSIGHT, USA) was used to excite each testing transducer with a 20 cycles tone burst sine signal and the frequency of the tone burst signal varied from 300 kHz to 1500 kHz with the step of the 5 kHz. A calibrated hydrophone (IP-124, GEC Marconi Ltd, UK) is located in the far field of the transducer (150 mm away from the transducer front face) for capturing the transmitted signal. The input and received signal was displayed using an oscilloscope in the time domain. The TVR in frequency domain was obtained using Eq. (9).

The TVR spectra of the three devices are shown in the Fig. 15. The -6 dB transmitting operational bandwidth of these devices is calculated as 64.0 % for the SG fractal device, 50.3 % for the equivalent conventional composite design and 31.2 % for commercial transducer. This equates to a 27.2 % and 105.1 % bandwidth improvement by the SG fractal device. In terms of the sensitivity level, the peak gain of the SG fractal device is 3.8 dB higher than the conventional composite design. However, the peak gain of the SG fractal device is 1.9 dB lower when compared to the commercial transducer, which is due to the significant difference in active aperture areas of each device.

C. Reception Response Measurement

In order to test the performance of the SG fractal device in reception mode, a broadband 9 μm customised PVDF transducer was used as a transmitter for generating a common acoustic signal and a calibrated hydrophone was initially used as the reference receiver. The field pressure characteristic generated by the PVDF transmitter was measured by the calibrated hydrophone first. Once a calibrated reference signal was recorded, the PVDF transmitter was replaced by each of the three devices and the field pressure measured. The distance between the reference hydrophone and the receiving device was maintained at 150 mm. The OCV response can be calculated using Eq. (10) and the resulting measured spectra are shown in Fig. 16.

D. Pulse Echo Response Measurement

In order to further validate the advantage of designing a composite ultrasound transducer using a fractal geometry, the pulse-echo response of each device was measured experimentally. The transducer was positioned in the water tank and a flat glass reflector with thickness of 50 mm was placed in the far field of the transducer, which is 100 mm away from the transducer front face. The pulser / receiver (5052 PR, Panametrics, USA) was used to excite each transducer and then receive the reflected echo signal. The received echo signal was amplified with a gain of 20 dB by the pulser / receiver and displayed using an oscilloscope. Because the active aperture area is different between these three devices, the measured time domain waveforms were normalized with respect to the transducer active area and are shown in Fig. 17. The resulting frequency responses are shown in the Fig. 18.
First of all, the modelling of the SG fractal device was designed and backing to improve the reception mode compared to the conventional transducer. Secondly, it is important to note that in this work neither of the 1-3 composite or SG fractal devices has been backed, whereas the conventional device incorporates both matching and backing to extend bandwidth. Therefore, the device comparison is not direct, with the commercial device used to provide a known benchmark performance against which the other devices can be compared. This is particularly evident in Fig. 17, where the axial resolution of the commercial device would highlight this device for conventional imaging applications. Similarly, the pseudo-random composite, as developed by Yang et al. [20], incorporates both matching and backing layers has a measured 6dB pulse-echo bandwidth of 61 %, whereas the unbacked fractal composite in this paper has a measured 6dB pulse-echo bandwidth of 47.5 %. Nevertheless, the SG device has achieved a wider operational bandwidth compared to the equivalent standard 1-3 composite and hence, the addition of a backing layer in future designs should provide additional damping to improve the axial resolution performance and increase the operational bandwidth.

There are two main challenges in manufacturing this SG fractal device due to the limitation of the 3D printing and ceramic dicing technique, which would have effect on the composite performance. First of all, the mould needs to be designed carefully and 3D printed precisely in order to make sure the individual pillars can be placed accurately into the mould and importantly, they must also stay in a vertical position during the remainder of the fabrication process. Secondly, it is important to note that in this work neither of the 1-3 composite or SG fractal devices has been backed, whereas the conventional device incorporates both matching and backing to extend bandwidth. Therefore, the device comparison is not direct, with the commercial device used to provide a known benchmark performance against which the other devices can be compared. This is particularly evident in Fig. 17, where the axial resolution of the commercial device would highlight this device for conventional imaging applications. Similarly, the pseudo-random composite, as developed by Yang et al. [20], incorporates both matching and backing layers has a measured 6dB pulse-echo bandwidth of 61 %, whereas the unbacked fractal composite in this paper has a measured 6dB pulse-echo bandwidth of 47.5 %. Nevertheless, the SG device has achieved a wider operational bandwidth compared to the equivalent standard 1-3 composite and hence, the addition of a backing layer in future designs should provide additional damping to improve the axial resolution performance and increase the operational bandwidth.

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difficult to cut triangular in small sizes and time consuming to manually place small sized pillars into the mould. As the results, there is a possibility that pillars may not stand vertically in the 3D printed mould, which might cause some negative influence on the transducer’s performance. For example, according to the experimental results, the SG composite still exhibits an improved bandwidth in reception and pulse-echo modes when compared to the conventional composite, but the improvement is no longer as apparent as what was predicted in the simulation results. Due to these manufacturing limitations, it would be very difficult and time consuming to manufacture this kind of SG fractal device in a higher fractal generation level or at a higher operating frequency range (above 1 MHz). However, one reason that the self-similar fractal geometry would still be a valuable choice compared with a random distributed geometry is that the fractal geometry can be generated by following a simple algebraic rule, which facilitates analyses of the transducer performance within the design space. Future SG fractal transducer designs should consider higher generation levels operating at frequencies above 1 MHz, which will lead to a finer composite microstructure. This will not only offer the potential to introduce a further extension of the operating bandwidth across a wider range of applications, but also reduce the pillar aspect ratio of the triangular pillars in higher generation levels, which will result in a reduction of the antiphase behavior and an enhancement of the surface dilation quality of the device. To achieve this the use of more advanced fabrication techniques will be required. Two potential solutions that could be considered are: 3D printing of the piezoelectric ceramic microstructure [34]; or using a programmed laser cutting technique to machine the bulk ceramic [35].

In summary, based on the evidence from the FE simulation and experimental results shown in this paper, the operational performance of a piezoelectric composite ultrasonic transducer can be improved by using a fractal geometry as the microstructure of active layer. This is due to the multiscale active elements within the fractal composite structure.

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