A WIDEBAND THERMO-ACOUSTIC SOUND GENERATOR ON NANOPOROUS POLYMERIC SUBSTRATE

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INTRODUCTION

Ultrasonic transducers operating in air are important components in systems used for ranging, surveillance, object identification, and air flow measurement [1]. In ranging and object identification, a wideband transducer is needed in order to achieve a better axial resolution. Some of the most commonly used ultrasonic sources are inherently resonant and hence narrowband. In case of thermo-acoustic sound generator (thermophone) electrical energy is converted to sound waves through Joule heating of a resistor without any mechanical vibration, thus allowing for a wideband operation [2]. Recently, there has been a renewed interest in this mode of sound generation. These efforts include various structures consisting of a thin conductor (e.g., aluminum, carbon nanotubes, ITO, and graphene) deposited on thermally insulating substrates such as porous silicon, polyethylene-terephthalate, and paper [3–6]. Many of these methods rely on complicated material and fabrication processes, which are not compatible with standard CMOS and other common microfabrication techniques. Here, we report on a thermophone using a thin metallic layer deposited on a nanoporous polymeric substrate. The fabrication method is simple, low-temperature, and compatible with active electronics.

DEVICE STRUCTURE AND FABRICATION

The thermophone (Figure 1) consists of a mechanical support (silicon, glass, etc.) coated with a thermally insulating nanoporous polymeric layer covered by an electrically conductive thin metal layer. When current is passed through the resistor, temperature of the metal rises due to Joule's heating, thus heating the surrounding air. Since the thin metal layer has very low heat capacity, when excited with alternating current (frequency f), it results in rapid variation of temperature leading to expansion and contraction of surrounding air at doubled frequency ($2f$), generating sound waves.

Figure 1: Schematic of the thermo-acoustic ultrasonic sound generator

Figure 2: Fabrication process

The performance of thermophone is highly dependent on the properties of thermal insulating layer. This layer helps in efficient transfer of heat to the air. A nano-material with adjustable porosity (and thus thermal conductivity) yields a better control over device performance.

Figure 2 shows the fabrication process. For our experiments, we used glass substrate and air-dried hydrogel [Poly(mAA-co-AAm)] as the nanoporous layer [7]. One can easily control the porosity of the gel by adjusting the ratio of cross-linker of its precursors. Although air-drying leads to collapse of porous structure, some porosity is expected to be retained (complete retention of porosity can be achieved through critical point drying). The thickness of the hydrogel can be controlled by adjusting the weight applied while curing the gel (a weight of 9 g resulted in 14 μm thick gel after drying). Finally, a thin layer of gold (40 nm) was patterned by shadow masking. Figure 3 shows photograph of a fabricated device.

RESULTS AND DISCUSSION

The hydrogel based thermophone was characterized in an anechoic room using a high-frequency condenser microphone. Figure 4 depicts the experimental set up. A sinusoidal voltage signal ($4.5 V_{pp}$) was applied across the serpentine resistor and generated acoustic signal was recorded at a distance of 30 mm.

Figure 3: Optical photograph of fabricated prototype

Figure 4: Schematic of experimental set up

Figure 5(a) shows input and output signal on the same plot with the output sound wave double the input signal frequency. Figure 5(b) shows sound pressure level (SPL) obtained at various frequencies. Input power was kept constant at 0.511 W for all the measurements. The performance of the device remains consistent up to 80 kHz (limited by the microphone used in the experiment).

It is not straightforward to compare the efficiency of our device with other acoustic devices due to difference in powering mechanism. Output SPL of our device is proportional to input power, while that of piezoelectric or electrostatic based acoustic devices is proportional to input voltage. In case of electromagnetic micro-speaker [8], SPL of 93 dB at 5 kHz has been reported at input voltage of 1.5 V (320 mW power). The piezoelectric micro-machined ultrasonic transducer shows a peak SPL of 85 dB at 0.4 V and 214 kHz [9]. Unlike thermophone, electromagnetic and piezoelectric based devices, which rely on mechanical vibration,

Figure 5. (a) SPL and Input power relations. Input at 20kHz generates output at 40kHz, which double the frequency, (b) Frequency response of SPL.

show a peak performance near the resonance but output signal attenuates before and after the resonant frequency. The performance of thermophone consistent over at least 80 kHz is a major advantage over these conventional ultrasonic transducers used for imaging or in-air ranging applications. Further, the structure and fabrication process presented here is simple enough to be adapted for miniaturization of the device. Although frequency doubling behavior of thermophone is somewhat inconvenient for audible speaker application, one can easily circumvent the problem by using an electronic circuit that reduces input frequency to half before the input [10].

CONCLUSIONS

We presented a simple, low-temperature method for fabricating a wide-band (>80 kHz) thermo-acoustic sound generator on a nanoporous polymeric substrate. We were able to achieve up to 80 dB of sound pressure level with input power of only 0.511 W. One can easily control the parameters such as gel thickness, porosity, and metal thickness to further improve the performance. Wide-band ultrasonic performance, simplicity of structure and scalability of the fabrication process make this device suitable for a wide range of ranging and imaging applications.

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