A Compact, Low-Power, and Electromagnetically Actuated Microspeaker for Hearing Aids

Sang-Soo Je and Junseok Chae, Member, IEEE

Abstract—In this letter, we present an electromagnetically actuated microspeaker with microelectromechanical systems (MEMS) technology to reduce form factor, cost, and power consumption in hearing aid applications. The microspeaker has multilayer copper coils, a NiFe soft magnet on a polyimide membrane, and a NdFeB permanent magnet on the perimeter. The coil impedance is measured at 1.5 Ω and shows a very flat response across the audio frequency range. The device operates at a very low power, the lowest in MEMS speakers, comparable to that of the macrosize counterparts. A single-turn microspeaker with a diameter of 2.5 mm consumes 11.6 and 0.13 mW to generate a sound pressure level of 129 and 106 dB at 1 kHz, respectively. The measurement uncertainty is less than 10%, and the reproducibility is within 36% among the tested devices.

Index Terms—Acoustic device, acoustic device fabrication, actuator, hearing aids, loudspeaker, microactuators, microelectromechanical systems (MEMS), micromachining, microspeaker.

I. INTRODUCTION

SOCIETAL stigma is the major factor why people, particularly young patients, are reluctant to wear hearing aids [1]. Completely-in-the-canal (CIC) hearing aids are most attractive in minimizing the societal stigma while they impose on stringent size requirement to minimize the power consumption of all devices in a small unit. Among various actuation mechanisms, the magnetic reluctance and electromagnetic actuation mechanisms are the most power efficient when generating a 106-dB sound pressure level (SPL) at a distance of 13 mm from the ear drum [2]. The magnetic reluctance actuation mechanism is a unique way to generate large membrane vibration while consuming very little power [3]. However, manufacturing processes for building magnetic reluctance speakers are complicated. By contrast, electromagnetic cone-type magnetic speakers have manufacturing processes that are compatible with microfabrication technology, given the size limitation of CIC hearing aids. Power consumption is one of the most critical parameters in hearing aids: Microspeakers consume up to 50%–95% of the entire power supply in hearing aids [4]. To prolong operation, it is crucial to have small yet power-efficient microspeakers. Several microelectromechanical systems (MEMS) microspeakers have been introduced in the past [3], [5]–[7]. Their power consumption, however, is still very high: an order of magnitude higher than their macrosize counterparts.

In this letter, we present an electromagnetically actuated microspeaker using MEMS technology to reduce form factor, cost, and power consumption.

II. DEVICE DESIGN, FABRICATION, AND EXPERIMENTAL SETUP

A. Device Design

Fig. 1 illustrates the electromagnetically actuated MEMS microspeaker for hearing aids. The microspeaker has a polyimide-suspended membrane at its center and a permanent magnet on its perimeter. The membrane has multilayer copper coils around a soft magnet core. The coils allow the membrane to vertically actuate with the Lorentz force generated by the external magnetic field and flowing current in the coils. The soft magnet core helps focus the magnetic field to achieve larger actuation. The external magnetic field is provided by a custom-made rare Earth NdFeB magnet that is manually glued to the chip perimeter.

B. Fabrication Process

The fabrication flow of the microspeaker is described in Fig. 2(a). 1) A 15-µm-thick polyimide membrane is spun, patterned on a silicon wafer, and cured in an oven at 350 °C. Seed layers (Ti/Au/Ti) are deposited using a dc sputter, and 10-µm-thick copper coils are electroplated on the patterned polyimide. 2) Via holes are defined using SU-8 to connect the first- and second-layer coils. Another 10-µm-thick polyimide layer is spun, patterned, and cured in an oven at 350 °C. Then, seed layers (Ti/Au/Ti) are deposited using a dc sputter, and the second 10-µm-thick copper coils are electroplated. 3) A 15-µm-thick Permalloy is electroplated at the center of the membrane.
4) The membrane is released by etching the back side of the silicon wafer using deep reactive ion etching. Fig. 2(b) shows a fabricated 4 mm \( \times \) 4 mm size device with a U.S. dime. After the microfabrication, a permanent magnet with inner and outer diameters of 3 and 5 mm is placed on the perimeter of the coils and glued on the chip. The magnet is made of NdFeB (from the Quadrant Magnetics group), with a high flux density of 1 T.

C. Experimental Setup

The membrane displacement is characterized by an optical interferometer (from OPTRA, Inc.) controlled by LabVIEW to automatically collect displacement data. The interferometer is supplied by a single power supply (12 V) and can resolve 20 nm with amplitude in the range of 10–500 \( \mu \)m up to 100 kHz [8]. To collect valid data, the interferometer should be placed within 3 mm from the device, which is controlled by a micromanipulator. The micromanipulator (from Newport Corporation) has a resolution of 1 \( \mu \)m in the \( x\), \( y\), and \( z\) directions. The readout of the interferometer is set up, so that 100 mV is equivalent to 1-\( \mu \)m membrane displacement.

III. Characterization and Discussion

The measured coil impedance of the single-turn device is only 1.5 \( \Omega \), which is much smaller than prior MEMS arts, and shows a flat response over the audio frequency range. The resonant frequency of the membrane is far away from the audio frequency range. At 1 Hz, the measurement uncertainty of the single- and two-turn devices is less than 10%. The displacements are linear (\( R^2 > 0.98 \)), and the peak displacement of a two-turn device, i.e., 2.2 \( \mu \)m, occurs at 88 mA. Major measurement uncertainty factors come from the placement of a permanent magnet and the alignment of the interferometer to the center of the membrane [2]. According to ANSYS simulations, approximately 27% less displacement is caused by the inaccurate assembly of the permanent magnet by 0.75 mm (3-dB SPL loss), and 23% less displacement is due to the misalignment of the laser on the membrane by 0.75 mm (2.3-dB SPL loss). From these two uncertainty sources, it is possible to have up to 50% less displacement, corresponding 5.3-dB SPL loss in the worst case. The reproducibility of the four devices is 32% and 36% at 1 Hz and 1 kHz, respectively. Fig. 3 shows the input power versus output SPL at different frequencies. SPL is calculated from the membrane displacement measured by the interferometer. At 1 kHz, the fabricated devices generate 90-dB and 106-dB SPLs using only 8 \( \mu \)W and 0.13 mW, respectively. Table I summarizes the specifications of the reported macro/microspeakers and the fabricated microspeaker. We excluded piezoelectric and electrostatic actuators, because their low conversion factor and high input voltage, respectively, make them unattractive for hearing aid applications. Most microdevices for hearing aids have adopted the electromagnetic actuation principle due to its high efficiency and powerful sound generation. With a membrane thickness in the range of 5–80 \( \mu \)m, microspeakers actuate membranes from 4 to 12 \( \mu \)m and generate 50- to 106-dB SPL in the human eardrum over audio frequency ranges [3], [5]–[7]. The measured power consumption of the microspeakers is lower by a factor of at least four compared to previously reported MEMS speakers and to that of the existing macrosize counterparts. The low-power and small-size microspeaker would potentially be a good fit for hearing aid applications.

IV. Conclusion and Future Work

A compact and low-power MEMS microspeaker for hearing aids has been fabricated using magnetic actuation technology. The coil impedance is measured to be as low as 1.5 \( \Omega \) and shows a very flat response over the audio frequency range. The displacements are linear up to the 88-mA input current for single-turn and two-turn devices. The measurement uncertainty is less than 10%, and the reproducibility is less than 36% among the tested devices. The device operates using a very low power, requiring, at maximum, tens of milliamperes. A single-turn microspeaker with a diameter of 2.5 mm consumes 11.6 mW of the battery power at peak displacement to generate 129-dB SPL and 0.13 mW to generate 106-dB SPL at 1 kHz. Future work includes reducing the size of the microspeaker by replacing the macrosize permanent magnet with a microsize sol gel permanent magnet [10]–[12]. The sol gel permanent magnet
could very precisely be assembled using a flip-chip bonding technique, eliminating misalignment issues that contribute to measurement uncertainty.

ACKNOWLEDGMENT

The authors thank Mr. Y. Yang, Ms. R. Steele, Knowles Electronics, and the Center for Solid State Electronics Research (CSSER) staff at Arizona State University for their helps.

REFERENCES