Micro and Nano Engineering 7 (2020) 100050

Contents lists available at ScienceDirect

Micro and Nano Engineering

journal homepage: www.journals.elsevier.com/micro-and-nano-engineering

Research paper

Design, fabrication and characterization of piezoelectric cantilever MEMS for underwater application

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ARTICLE INFO

Keywords:
MEMS
Cantilevers
AlN
Piezoelectricity
Laser Doppler Vibrometer
Hydrophone

ABSTRACT

This work shows a preliminary microfabrication route for a novel directional hydrophone based on a cross-shaped design of piezoelectric cantilevers. A thin layer of aluminum nitride (AlN) using Molybdenum (Mo) thin film as electrodes will be exploited as piezoelectric functional layer for the microfabrication of a cantilever-based ultrasonic micro electro mechanical system (MEMS) hydrophone. A parameterized simulation based on length of these cantilevers between 100 and 1000 µm allowed to set the first resonant mode between 20 kHz and 200 kHz, the desired underwater ultrasonic acoustic range. The microsystem was designed with cantilevers facing each other in a cross configuration in order to have novel MEMS hydrophone with an omnidirectional response. In order to investigate the first resonance frequency mode and displacement measurements, a Laser Doppler Vibrometer was used and good agreement between simulations and experimental results was achieved. Responsivity and directionality measurements of the piezoelectric MEMS cantilevers were performed in water. Maximum sensitivity up to −153 dB with omnidirectional directivity pattern was achieved by fabricated MEMS sensor.

1. Introduction

Acoustic monitoring of marine organisms especially those emitting sounds (e.g. dolphins, whales) fill a significant ecological role as top predators in pelagic ecosystem. Production and reception of underwater acoustics are critical for delphinids to navigate, find food, coordinate with others, and detect predators. By recording and studying their sounds, insight about their ecological and trophic dynamics can be obtained. Ability to enhance signal identification and processing of acoustic datasets of dolphins in the wild marine environment will receive an advancement by underwater acoustic [1]. Humans will be gradually more and more dependent on the marine resources, and underwater acoustic detection equipment with excellent performance is necessary [2].

Hydrophone's applications have some limitations in term of desired resonance frequency, sensitivity, device shape and directionality. Their miniaturization is the key element and has been a subject of recent research [3–5]. Though, miniaturization of most conventional acoustic transducers has led to limitations in terms of resolution, sensitivity, high impedance at low frequencies and low performance [6]. In this respect, MEMS piezoelectric ultrasonic transducers represents an excellent alternative [7–9]. Indeed, thin films of piezoelectric materials have attracted attention because they have been employed for obtaining compact micro-electro-mechanical systems (MEMS) with precise response at characteristic frequencies in the ultrasonic range and with good directivity pattern.

Aluminum nitride (AlN) piezoelectric MEMS cantilevers are very attractive for ultrasonic transducer due to compatibility with CMOS processing and low power operation [10]. The combination of microfabrication techniques for integrated circuits (ICs) [11,12] and MEMS design permits the realization of ultrasonic MEMS hydrophone exploiting signal processing circuits, such as amplifier and filter circuits, for the improvement of sensitivity and directionality.

This paper shows the fabrication and characterization of aluminum nitride (AlN) based piezoelectric MEMS cantilevers for directional underwater acoustics on silicon substrates. Finite Element Method is used to design, to simulate and to investigate the properties of the piezoelectric cantilevers. As a result, an optimized hydrophone was fabricated and characterized. The proposed and fabricated hydrophone is the first piezoelectric cantilever-based hydrophone and it was designed for underwater application in the frequency band from 20 kHz up to 200 kHz. Its performance and compactness make us to envision its employment in underwater acoustics for monitoring of marine cetaceans and ultrasound communications.

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https://doi.org/10.1016/j.mne.2020.100050
Received 3 March 2020; Received in revised form 29 March 2020; Accepted 30 March 2020

Table 1
Materials properties and thickness used to perform COMSOL simulations for all MEMS piezoelectric cantilevers.

Materials [15]	Thickness	Relative permittivity	Poisson ratio	Density [g/cm^3]	Young modulus [GPa]
Molybdenum	200 nm (Top & Bottom)	1	0.29	10.1	315
Aluminum Nitride	2 µm	9	0.27	3.3	348
Parylene	1 µm	–	0.4	1.289	2.8

2. Sensor design

In hydrophone applications, piezoelectric transducer exploits the direct piezoelectric effect, in which ultrasonic mechanical signals traveling underwater are converted into electrical signals. Performance of the hydrophone is mostly assessed in term of frequency range, sensitivity and directivity pattern [13]. The range of frequency of MEMS transducer needs to be between 20 kHz to 200 kHz, the desired underwater ultrasonic acoustic range. In order to define the geometry of piezoelectric cantilevers, it should be taken in mind that material thickness and length of cantilevers are the main key parameters for designing the frequency response. Therefore, any changes in these two parameters can affect the desired ultrasonic frequency range of the device, in contrast to the cantilever width, not having significant effect on the resonance frequency. A 2 µm thick AlN layer for the cantilever was fixed because it ensures a better tradeoff between maximizing voltage response and obtaining mechanical flexibility [19]. Molybdenum (Mo) thin films of 200 nm thickness are used as top and bottom electrodes and parylene coating of 1-µm thickness is exploited for waterproof sealing. In parallel, cantilever width of 70 µm was the best choice for limiting the under etching in the cantilever hinge due to an isotropic dry etching in order to avoid mechanical breaking. Therefore, a parametric sweeping on the cantilever length of the piezoelectric MEMS was designed by Finite Element Method (FEM) for tuning the resonance frequency in the desired range [14], exploiting the material properties listed in Table 1.

Different length of cantilevers, starting from 100 to 1000 µm, were simulated in water environment to find out the first resonance frequency mode in water as shown in the Fig. 1(a).

As expected, Fig. 1(a) shows that the first resonance frequency of the cantilevers decreases as its length increases. Starting from these simulations, only cantilever lengths ranging between 100 and 300 µm, corresponding to the ultrasonic frequency range, will be realized.

3. Sensor fabrication

Cantilevers with length of 100, 150, 200, 250 and 300 µm were fabricated by standard MEMS process on silicon wafer. A thin layer of Molybdenum (Mo) was first deposited on silicon wafer by (DC) magnetron sputtering with thickness of 200 nm as bottom electrode. Then a 2 µm thick AZ5214E photo resist was spin coated and soft baked at 120C° for two minutes.

Mask aligner (SUSS MA8/BA8) at 135 mJ / cm^2 exposure for 20 s was used to define the bottom electrode as shown in Fig. 1(a). For development, MIF AZ826 was used for one minute and then washed with water. To remove the exposed Mo layer, dry etching is performed by inductively coupled plasma (ICP) with a gas mixture composed by of Boron Trichloride (BCl_3, 45 sccm) and Nitrogen (N_2, 20 sccm). The RF powers applied to platen and coil were 250 W and 600 W, respectively. Then, two layers of 2 µm of Aluminum Nitride (AlN) and 200 nm of Molybdenum (Mo), respectively, were deposited by sputtering.

TI35E photoresist with thickness of 4-µm was deposited by spin coater on the grown sample and then soft baked at 95C° for 2 min. Exposure of 140 mJ/cm^2 by mask aligner was performed for top electrode definition as shown in Fig. 1(b) followed by MIF AZ826 soaking for development. Molybdenum (Mo) top layer was etched by ICP with the same recipe above mentioned. Finally, an Inductively Coupled Plasma (ICP) dry etching was performed for the Aluminum Nitride (AlN) etching, based on chlorine gas mixture of Boron Trichloride (BCl_3, 100 sccm) and Argon (Ar, 25 sccm). The RF powers applied to platen and coil were 250 W and 600 W, respectively.

Similarly, for cantilever releasing, a similar photolithography process as for bottom electrode was adopted. For releasing the cantilever, ICP etching of silicon with SF_6 at very low temperatures and at very low pressures was used to produce isotropic etch profiles of silicon as shown in Fig. 1(c), which help the cantilever to be released from the substrate. 700 sscm of SF_6, coil power of 2600 W and pressure of 100 mTorr at temperature 18C° were applied for silicon etching.

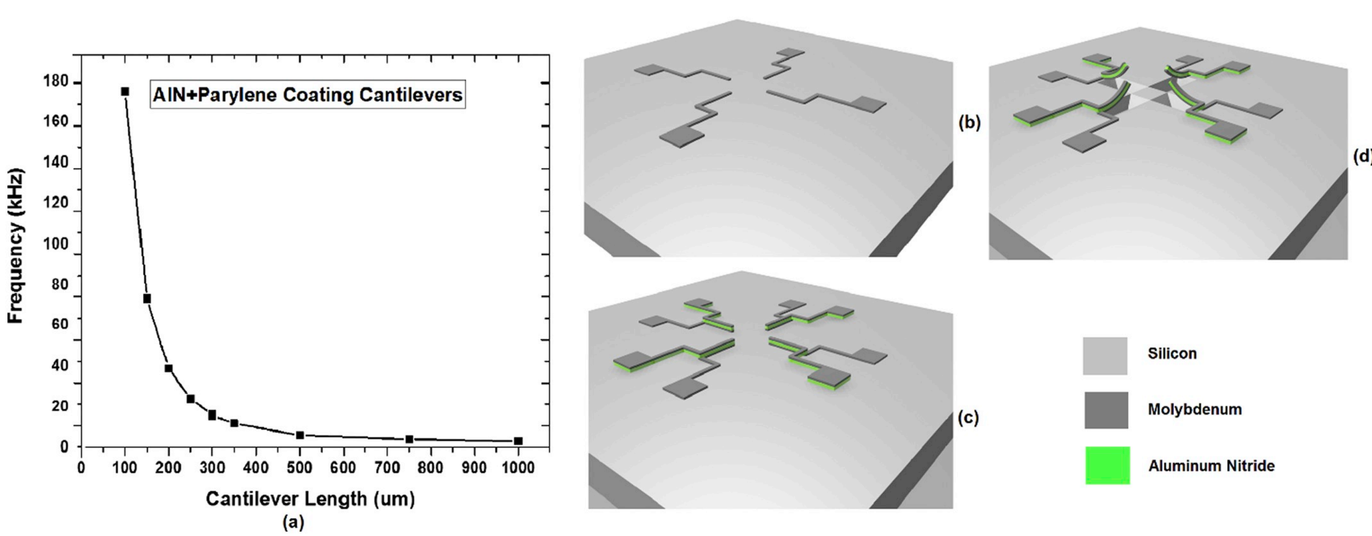

Fig. 1. (a) COMSOL simulation of parylene coated AlN cantilevers first resonance mode frequency in water as function of their length. (b) Molybdenum bottom electrode definition. (c) Aluminum nitride piezoelectric layer and molybdenum top electrode definition. (d) Release of cantilever from silicon substrate.

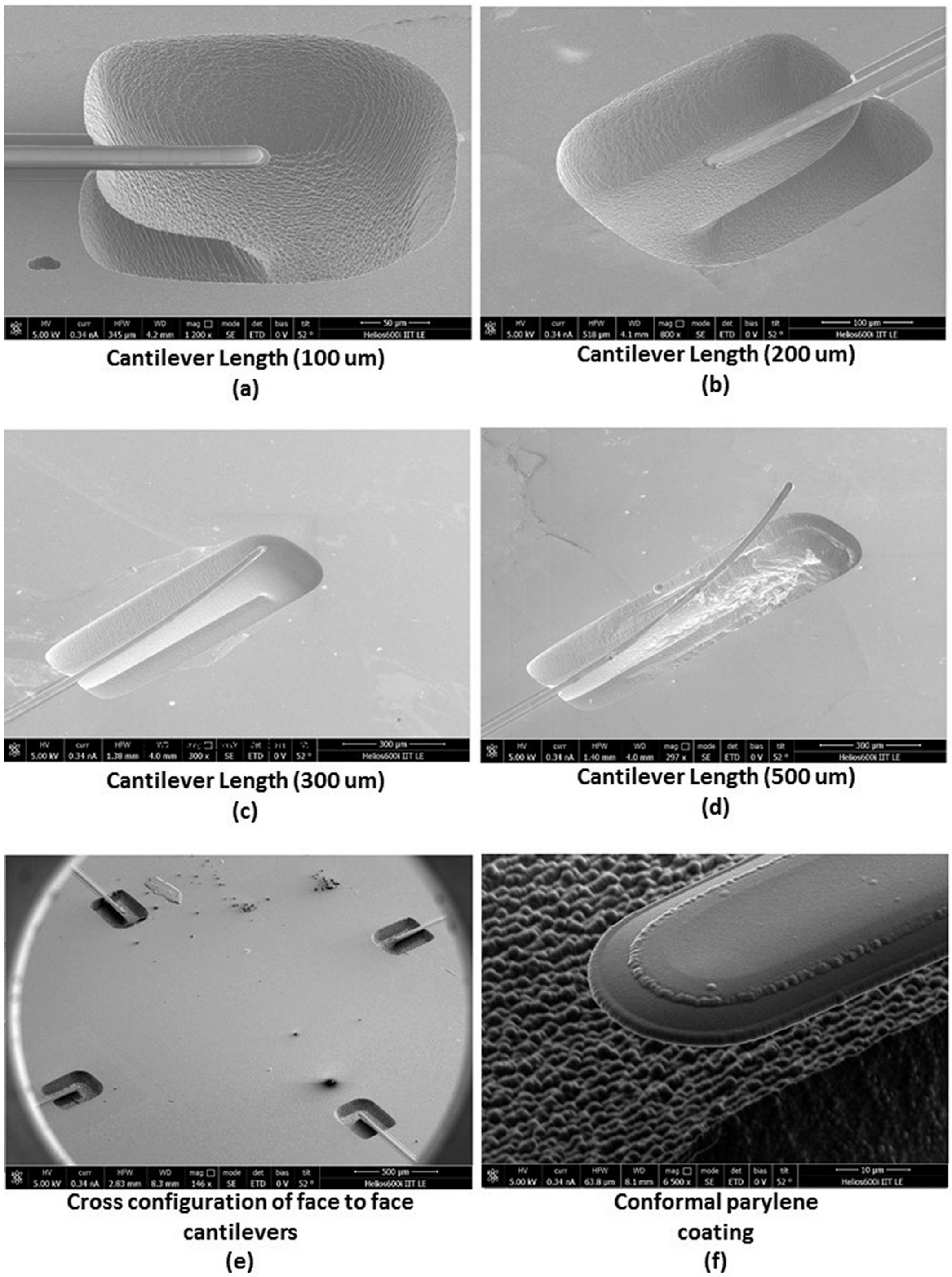

Fig. 2. SEM images of MEMS fabricated cantilevers showing an increasing bending stress with respect of length of; (a) 100-μm. (b) 200-μm. (c) 300-μm. (d) 500-μm (showing maximum stress with clear visible bending and out of frequency range target). (e) Face to face, cross- configuration of four flat cantilevers with 300-μm length. (f) Cantilever tip showing conformal parylene coating of 1-μm thickness on the whole cantilever layer stack.

4. Sensor characterization

SEM images in Fig. 2 shows four different released cantilevers with length ranging between 100 and 500 μm. As the length of cantilever increases, the upward bending of the tip increases accordingly. This is in agreement with Stoney equation for cantilever, where the curvature C is expressed as in ref. [16]

$$C = \frac{1}{R} = \frac{6\delta}{Et^2}$$

where R is radius of curvature, E is the Young modulus, t is the thickness of the cantilever and δ is the surface stress, i.e. the intrinsic stress accumulated during the sputtering process, which causes the upward bending.

Laser Doppler Vibrometer (Polytec Vibrometer MSA500) analysis shows that the measured first resonance mode is in agreement with the simulated frequency of the cantilevers. The deviations between simulations and measurements was present only for one length. Measurements in Fig. 3(a) have been collected for different cantilevers lengths, ranging between 100 μm and 300 μm. In this length range, all

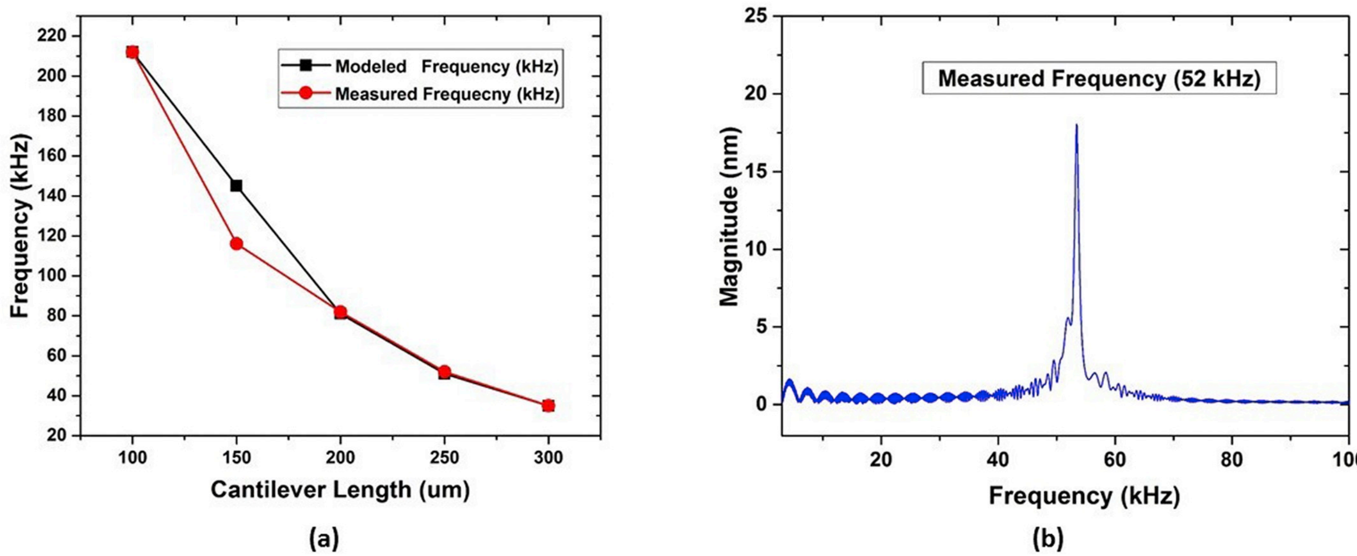

Fig. 3. (a) Laser Doppler Vibrometer measurements of MEMS fabricated cantilevers in comparison with modeled resonance frequency. (b) Frequency spectrum of the 250-μm long cantilever actuated at 5 V, peaked at 52 kHz in good agreement with simulation results (~51 kHz).

the cantilevers have very little stress and this stress neither have any effect on mechanical feature of cantilevers nor it shows any change of value of elastic modulus. Therefore, the related COMSOL simulations have been performed with the same material properties (see Table 1) and layer thicknesses for all the different cantilevers lengths, with a good agreement between experiment and simulated frequencies results. As an example, Fig. 3(b) reports the frequency spectrum of the 250-μm long cantilever actuated at 5 V in a range between 20 kHz and 200 kHz. Modeled frequency of the cantilever was 51 kHz while the measured was 52 kHz.

5. Underwater characterization

5.1. Measurement set up

Characterization of hydrophone in terms of sensitivity and directionality was carried out by using echo pulse technique. All top and bottom electrodes are connected to 500 × 500 um^2 contacts pads where wirings are connected with a printed circuits board (PCB). To avoid short-circuits, the whole device including PCB and wires are coated with parylene-C of 1 μm thickness by means of room-temperature chemical vapour deposition (RT-CVD) achieved by PDS 2010 Lab coater system. This process allows performing underwater characterization making final device waterproof. Deposition parameters for MEMS piezoelectric cantilevers are set at vaporizer temperature of 175C°, a pyrolysis furnace temperature of 690C° and coating process pressure of 25-mTorr, respectively. PCB was successfully connected to instruments for measurements. Measurement set up consisted of a function generator supplying a transducer emitting acoustic waves at 200 kHz, a fixed reference hydrophone (Onda HNP-1000) and the MEMS hydrophone under test placed on a rotary stage. The reference hydrophone was located close to the MEMS hydrophone in a water tank as shown in Fig. 4(a).

Under water testing was performed with train pulses emitted by the transducer biased at 400 Volts, pulse repetition frequency (PFR) from 1 to 5 kHz and pulse duration between 10 and 70 ns. Different key parameters such as temperature of water, environmental noise, depth of immersion and interface from acoustics reflection [17] have been constant during the measurements.

5.2. Peak output voltage response

Peak output voltage response for each cantilever as a function of pulse repetition frequencies was measured by an oscilloscope (Tektronix, MSO2000B) as shown in Fig. 4(b). The output voltage response of each cantilever increases with its length and is enhanced by higher pulse repetition frequency. A considerably increased output voltage response was recorded in bent cantilevers. In fact, cross sectional area of interaction between cantilever and incident acoustic waves increases super linearly with bending, generating higher voltages response as a consequence.

5.3. Sensitivity measurement

In order to perform sensitivity measurement, the voltage response of MEMS transducer was compared with the reference hydrophone response, according the sensitivity reference formula [18]:

$$S_{MEMS} = S_{ref}\,\frac{V_{MEMS}}{V_{ref}}\,\frac{\text{sine}kd}{\text{cose }kd}$$

where S_{MEMS} is sensitivity of the tested hydrophone and S_{ref} is sensitivity of reference hydrophone. V_{MEMS} and V_{ref} are the peak voltage response from MEMS and reference hydrophone respectively, k denotes the number of waves in a single wave train and d is the distance from surface of water to reference hydrophone and MEMS transducer. Fig. 4(c) shows sensitivity of the cantilevers at different pulse repetition frequency (1 to 5 kHz). As already shown, the sensitivity increases with the cantilever length and pulse repetition frequency. The maximum sensitivity was −153 dB for the longest cantilever (L = 300 μm) at 5 kHz pulse repetition frequency.

5.4. Directionality

Four identical cantilevers where positioned in a cross configuration and characterized in the same underwater experimental setup and placed on a rotary stage in order to measure the directivity pattern. The MEMS hydrophone signal response was measured every 15° rotation angles with respect to the source. Single bent and flat cantilevers show that each sensor has a cardioid response vs. angle with a sensing directionality aperture close to 160° along the cantilever length, as shown in the Fig. 5. Fig. 6 shows the Omni directionality mode, consisting of the sum of all the output voltage response from each cantilevers. As

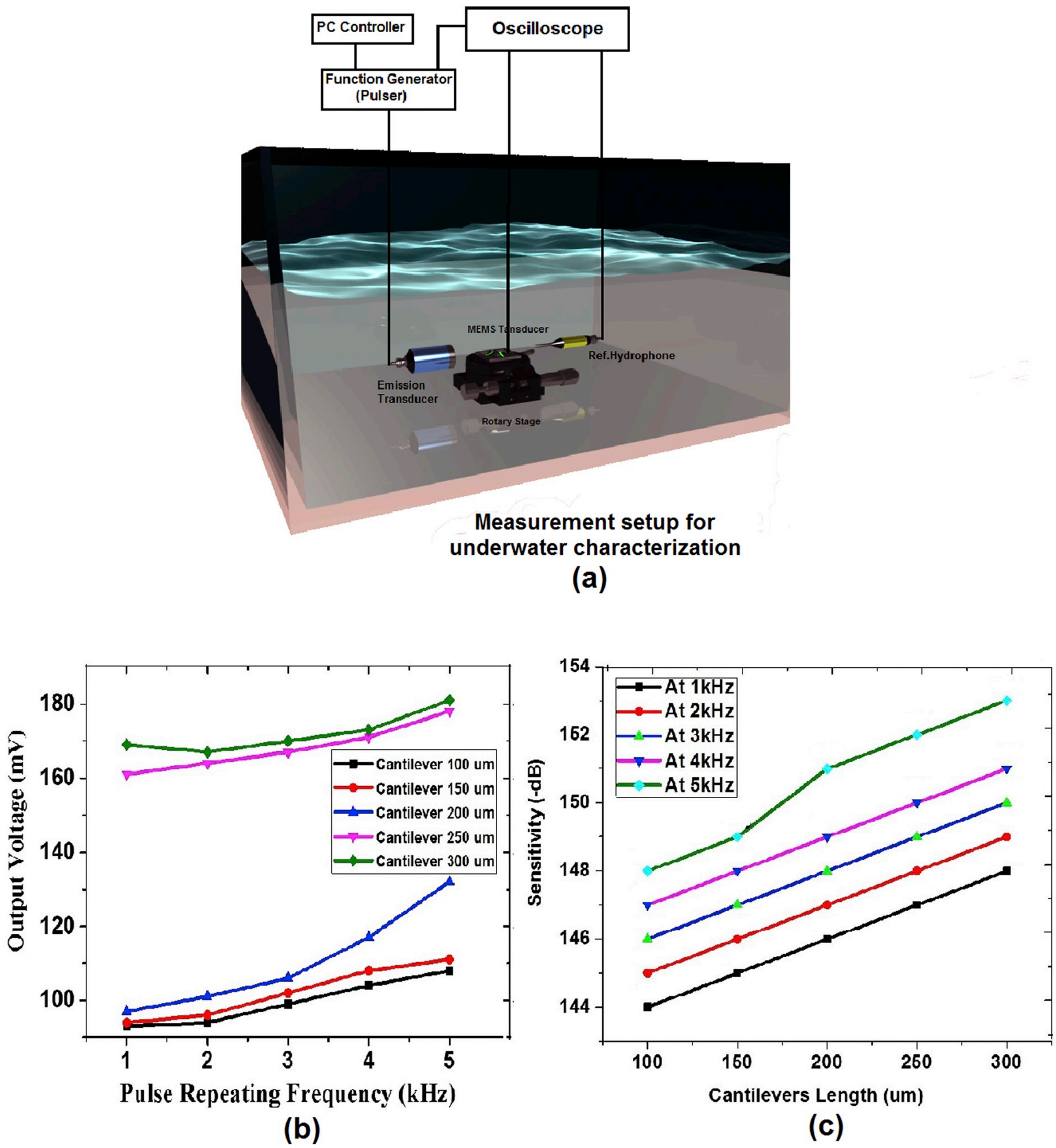

Fig. 4. (a) Schematic diagram of experimental setup for evaluating the performance of MEMS hydrophone. (b) Measured average output voltages response of the four cantilevers at different lengths and acoustic pulse repetition frequency. (c) Receiving sensitivity of each cantilever.

shown in the figure, in Omni directionality mode, under water acoustic signal from all directions can be equally detected. Moreover, bent cantilevers based hydrophone have higher voltage response, as compared to flat cantilevers.

6. Discussion and conclusion

In this work, design, fabrication and characterization of the first AlN-based MEMS piezoelectric ultrasonic hydrophone have been reported. The test results showed that four cantilevers in a cross configuration has high sensitivity in underwater ultrasonic frequency range, allowing to equally detect an acoustic source from all directions showing a clear novelty in its design and good performances with currently available hydrophones. Laser Doppler Vibrometer measurements were in agreement with modeled frequency. A study on different cantilever lengths allowed to compare a flat and an upward bent cantilever hydrophone, showing sensitivity improvement with length. Maximum output voltage response was 181 mV at 5 kHz pulse repeating frequency (PRF) and 400 V as transducer power supply voltage and it was obtained for the bent cantilever for an ultrasonic emission at 200 kHz. Highest sensitivity was −153 dB achieved at 5 kHz pulse repeating frequency (PRF) for the longest bent cantilever. These results demonstrate that sensor with bent cantilevers have more output voltage response, have higher sensitivity than flat cantilever for all wave directions. Cardioid pattern with direction for each single cantilever showed that each sensor is able to identify the acoustics source direction with a very large uncertainty (160°) along the cantilever length. Through Omni directionality pattern, the magnitude of the sound pressure can be determined in all the direction with the same sensitivity. In conclusion, MEMS piezoelectric transducers can be used as

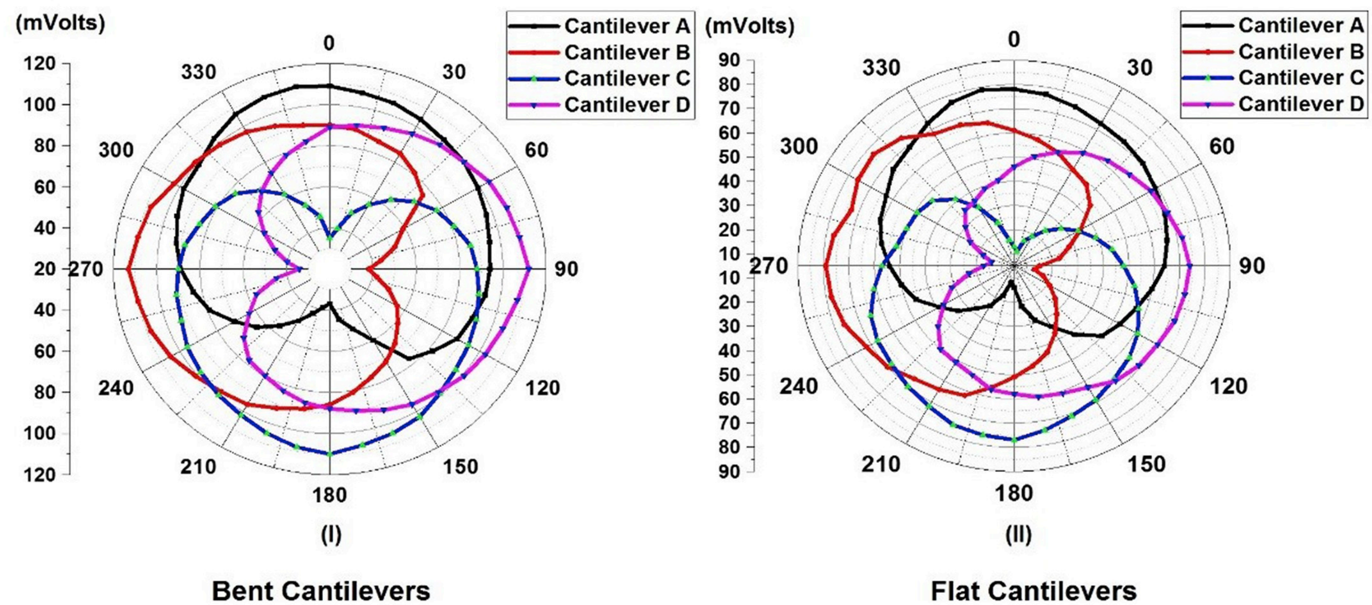

Fig. 5. Cardioid directionality pattern for bent and flat cantilevers.

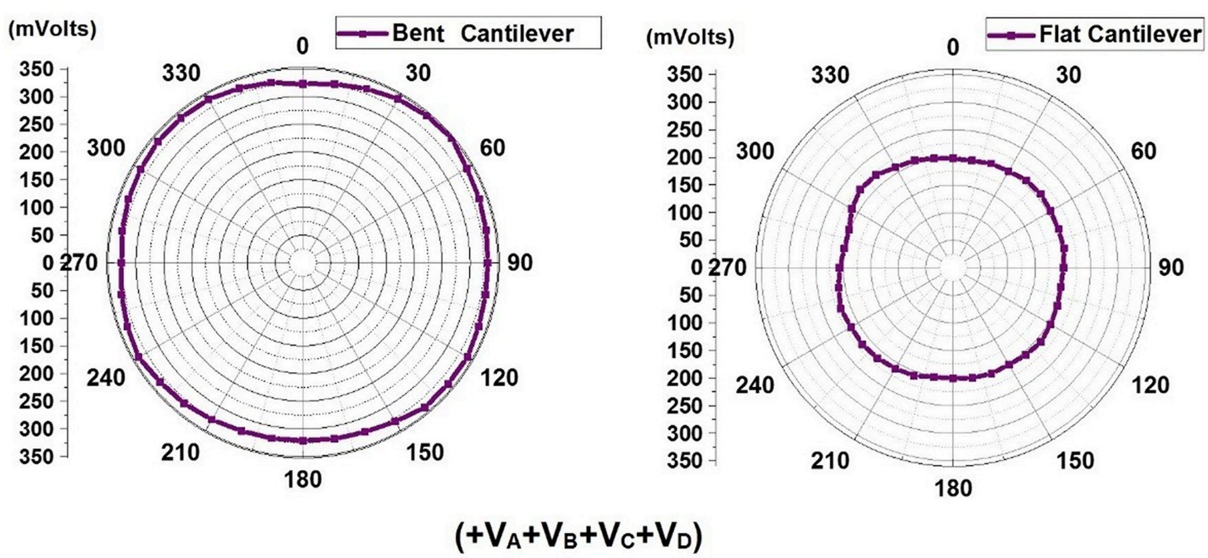

Fig. 6. Omni directionality pattern for bent and flat cantilevers.

ultrasonic hydrophones, able to sense both amplitude and directionality for underwater acoustics pulses. Cross-configurations with different cantilever lengths, sensitive to different ultrasound frequencies range, could be combined to promote higher directionality and wider ultrasonic range.

Credit author statement

B. Abdul, V.M. Mastronardi, F. Rizzi, M. De Vittorio: Conceptualization, Writing – original draft, Writing – review & editing **B. Abdul, V.M. Mastronardi, F. Rizzi:** Methodology, Investigation, Validation **B. Abdul, F. Rizzi**: Software, Formal analysis **B. Abdul**: Data Curation, Visualization **F. Rizzi, V.M. Mastronardi, A. Qualtieri, F. Guido. L. Algieri:** Resources **V.M. Mastronardi, F. Rizzi, M. De Vittorio:** Supervision

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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