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Sensors and energy harvesters based on piezoelectric thick films

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Abstract

The use of piezoelectric thick films based on lead zirconate titanate (PZT) deposited by screen printing and direct writing techniques on different substrates, including alumina, steel and silicon, for sensors and energy conversion is reported. Resonant sensors with contactless interrogation by means of a gated technique are experimentally demonstrated on humidity and temperature sensing. Energy harvesters from broadband vibrations based on multi-element arrays and nonlinear structures, and from rotational motion based on frequency up-conversion are described.

Keywords: Piezoelectric thick films; contactless resonant sensors; vibration and motion energy harvesting.

1. Introduction

A current trend in sensor development is to increasingly aim at providing radio-frequency signal transmission. Wireless is desirable in many applications, while it can be mandatory in closed volumes or mobile systems. Eliminating cables requires means to make energy available in the sensor unit for power supply. Batteries are one option, yet they have limitations such as the demand for periodical access for replacement/recharge. Two attractive alternatives exist, namely using passive sensors with energy supplied from an external interrogation unit, or powering the sensor through energy harvesting from the surroundings. Passive sensors with external readout typically establish a contactless short-range connection upon interrogation and can be suitable for hostile environments. Energy harvesting enables wireless sensor nodes with on-board active electronics supporting a certain degree of communication

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capability. The piezoelectric effect can be exploited both in passive resonant sensors with contactless interrogation [1], and in energy harvesters from mechanical sources such as vibrations and movement [2].

Devices belonging to both classes based on piezoelectric thick films on different substrates are presented after a short overview of thick film deposition techniques.

2. Piezoelectric thick films deposition methods

Among piezoelectric materials lead zirconate titanate (PZT) offers large piezoelectric effect and flexibility in the formulation. PZT pastes based on PbO or glass binders and organic vehicles are used in screen-printed thick films on alumina or metal substrates by the standard thick-film technology (TFT). Compared to other deposition methods, PZT films made in TFT have higher thickness, in the range of 10-100 μm. Alternatives to the standard TFT approach are being investigated for the low-cost deposition of PZT thick films on different substrates such as silicon, flexible metal shims, plastics or textiles [3].

To deposit films on substrates that cannot withstand the firing temperature of standard PZT pastes, PZT inks composed of commercial powders in a low-curing-temperature binder have been prepared. Fig.1a shows a film obtained from a PZT ink based on Piezokeramica-APC 856 powder screen printed on a 200-μm thick steel shim. The film has been cured at 150°C for 10 min and then poled at 5 MV/m at 130°C for 10 min. Electrodes are made by Ag polymeric ink. Besides screen-printing, approaches based on direct-writing technology are investigated. Results for a droplet-ejection method are reported in [4]. To avoid droplet splattering, a Sonoplot GIX Microplotter Desktop has been used to deposit by an ultrasonically driven micropipette a low-curing-temperature PZT ink on a MEMS silicon cantilever. Fig.1b shows the fabricated device with a detail of the PZT film before the deposition of the top electrode. The process has the potential to provide a resolution around 30 μm, but the ink formulation has to be further improved to avoid clogging of the micropipette and to increase repeatability.

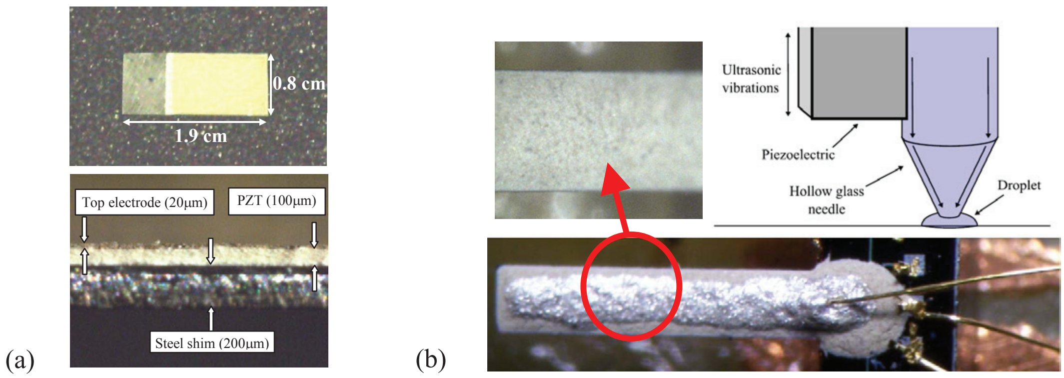

Fig. 1. PZT thick films strarting from a low-curing-temperature ink: (a) film screen printed on a steel shim; (b) film dispensed by utrasonic direct writing on a MEMS silicon cantilever (the inset shows the PZT film before the depostion of the top electrode).

Controlled microdispensing of PZT ink has also been obtained by a custom-made extrusion micronozzle around 100 μm in diameter, electronically driven by a stepper motor, mounted on a micropositioning system. Fig.2 shows an array of steel cantilevers of different lengths over which a PZT thick film and top electrode have been dispensed, and the impulse response to mechanical excitation of the poled device.

The films obtained from low-curing temperature inks at present feature piezoelectric coefficients d_{33} lower than 10 pC/N, which is at least one order of magnitude less than standard TFT PZT pastes.

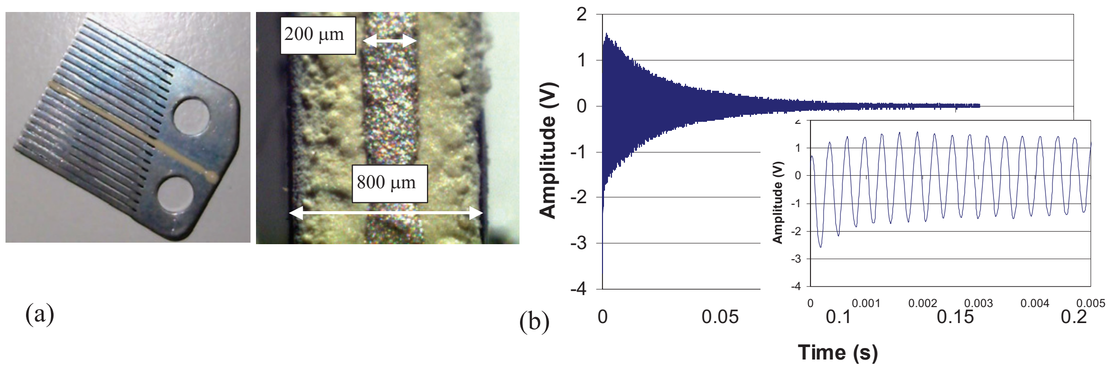

Fig. 2. Array of steel cantilevers of different lengths: (a) top view detail of PZT thck film and top electrode dispensed by the extrusion micronozzle; (b) voltage output under mechanical impulse excitation.

3. Contactless resonant sensors

In resonant sensors the measurand quantity alters the frequency and damping of an oscillating mechanical structure that can be brought into resonance using different techniques, including the piezoelectric effect. In resonant sensors, measurement information is carried by the readout signal on the time domain and not on its analog magnitude. This is advantageous for contactless readout which intrinsically introduce a dependence of the signal amplitude on the interrogation distance. The resonant frequency does not depend on the specific interrogation method adopted, making resonant sensing a robust approach for contactless operation.

Piezoelectric resonant sensors have been fabricated made by the superposition of a nonpiezoelectric substrate, specifically alumina, a bottom electrode layer, a screen-printed PZT film poled along its thickness, and a top electrode layer. The PZT film is acoustically coupled to the substrate, leading to a thickness-expansion composite resonator named resonant piezo-layer (RPL) sensor, which can be used as a bulk acoustic-wave sensor responsive to an acoustic surface load [5, 6].

Typical dimensions are 5 mm for the electrode diameter, 250, 10 and 90 µm for the thickness of the substrate, electrodes and PZT respectively. This results in a resonant frequency of around 6-7 MHz, while higher values can be achieved for thinner devices.

The sensor structure is shown in Fig.3a. A typical impedance spectrum around the first resonance is shown in Fig.3b together with the equivalent lumped-element electric model and values of the model elements.

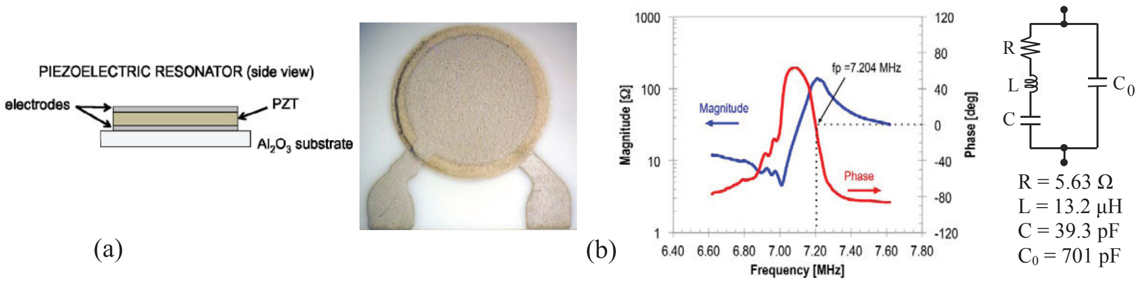

Fig. 3: Resonant piezo-layer sensor based on PZT thick film on alumina subsrate: (a) structure and picture; (b) typical impedance spectrum around fundamental resonance and equivalent lumped-element electric circuit and parameters.

The contactless interrogation principle of the sensor employs two electromagnetically air-coupled loop coils with the primary and secondary coils connected to the electronic readout unit and the sensor, respectively. The block diagram is shown in Fig.4a.

The developed interrogation method consists of a gated technique based on the separation in time of the excitation and detection phases. During the excitation phase the fundamental resonance is excited, while in the detection phase the excitation signal is turned off and the transient decaying response of the resonator is contactless sensed by measuring the voltage induced back across the primary coil.

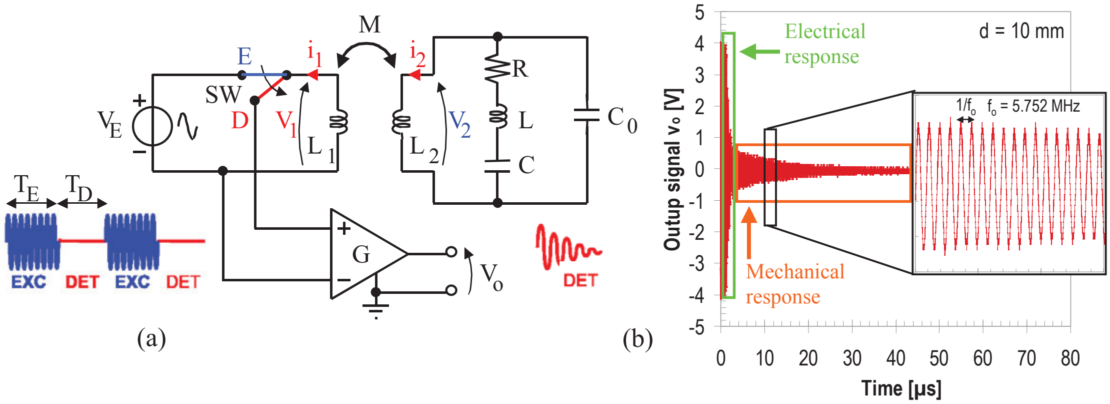

Fig. 4. Contactless gated interrogation technique for RPL sensors: (a) block diagram; (b) typical output signal.

A periodic square waveform is exploited as a gating signal to drive the switch SW. In the excitation phase, the gating signal sets the switch in the position E for a time interval T_E, during which a sinusoidal voltage with amplitude V_E and frequency f_E is applied to the primary coil generating a voltage V_2 at the secondary across the sensor. This drives the sensor into vibrations.

In the detection phase, the gating signal sets the switch to the position D for a time interval T_D, during which the sensor undergoes decaying oscillations with an initial amplitude inversely related to the offset between the excitation frequency f_E and sensor resonant frequency. A voltage V_1 is generated at the primary coil which, after amplification by a gain G, becomes the output voltage V_o.

With reference to Fig.4a, the system behavior in the detection phase, assuming that the current i_1 in the primary coil is zero due to high-impedance readout, can be described in the Laplace domain by:

$$I_2 = \frac{V_{m(0)} + sV_{e(0)} Z_m C_0}{Z_m(1+sC_0Z_2)+Z_2} = \frac{\left[\frac{v_{C(0)}}{s} - L i_{L(0)}\right] + v_{C_0(0)} Z_m C_0}{Z_m(1+sC_0Z_2)+Z_2} \qquad (1a)$$

$$V_1 = sMI_2 \qquad (1b)$$

where $Z_m = R+sL+1/sC$ is the impedance of the resonator motional, i.e. mechanical, arm, $Z_2 = R_2+sL_2$ is the impedance of the secondary coil including resistance, $M = K(L_1L_2)^{1/2}$ is the mutual inductance with K denoting the coupling coefficient between the coils, $V_{m(0)}$ and $V_{e(0)}$ are the motional and electrical initial conditions, respectively, at the time $t = 0$ of switching from the excitation to the detection phase.

Under the assumption that in the denominator of Eq.(1a) Z_2 can be made negligible with respect to $Z_m(1+ sC_0Z_2)$, the output voltage V_o in the time domain becomes:

$$V_o(t) = GM\left[V_{Ae}e^{-\alpha_e t}\cos(\omega_{de}t-\theta_e)+V_{Am}e^{-\alpha_m t}\cos(\omega_{dm}t-\theta_m)\right] \quad (2)$$

where $\alpha_e=R_2/2L_2$ and $\alpha_m=R/2L$ are the electrical and mechanical exponential attenuation rates, respectively, and $\omega_{de} = (1/L_2C_0 - \alpha_e^2)^{1/2}$ and $\omega_{dm} = (1/LC - \alpha_m^2)^{1/2}$ the damped electrical and mechanical natural angular frequencies, respectively. The amplitude and phase coefficients V_{Ae}, V_{Am}, θ_e and θ_m are functions of the initial conditions.

Eq.(2) shows that $V_o(t)$ is expected to be the sum of two damped sine waves. By detecting the motional response, the sensor series resonant frequency $\omega_s = 1/LC$ and quality factor $Q = \omega_s/2\alpha_m$ can be extracted.

The gated technique has the advantage that the detected sensor parameters are virtually unaffected by the coil coupling coefficient, therefore it can be robust against the interrogation distance. The mutual inductance M only enters as a scaling factor for the amplitude of $V_o(t)$.

The interrogation circuit has been set up with two wire loops with a diameter of 4 cm and L_2 and R_2 of about 200 nH and 0.3 Ω, respectively. An amplifier gain G of 5 has been used. The excitation signal V_E is 10 V_{pp} and $T_E = T_D = 0.1$ ms. The excitation frequency f_E is coarsely tuned to the sensor nominal resonance to maximize the energy coupling.

Fig.4b shows the typical measured $V_o(t)$ for a RPL sensor at an interrogation distance of 10 mm. The two damped sinusoids predicted by Eq.(2) are visible with the electrical time constant $1/\alpha_e$ much smaller than the mechanical $1/\alpha_m$. Measurements taken with a HP4194 impedance analyzer as a reference have resulted in $f_s = 5.755$ MHz and $Q = 150$ in agreement with the readout frequency f_o from the contactless interrogation equal to 5.752 MHz.

A RPL sensor functionalized with a hydrophilic film of PVP (Polyvinylpyrrolidinone) has been placed in a closed chamber under controlled humidity and contactless interrogated from outside, with the coils positioned about 1 cm apart separated by the Teflon chamber side.

Fig.5a plots the measured readout frequency f_o versus the values of RH obtained from a reference sensor (Gefran T6000) inside the chamber. The RPL works as a contactless mass-sensitive RH sensor.

Fig.5b shows the readout frequency f_o for an uncoated 7.2 MHz RPL sensor versus temperature with a linearly decreasing trend as expected [5]. The results demonstrate temperature sensing with contactless interrogation.

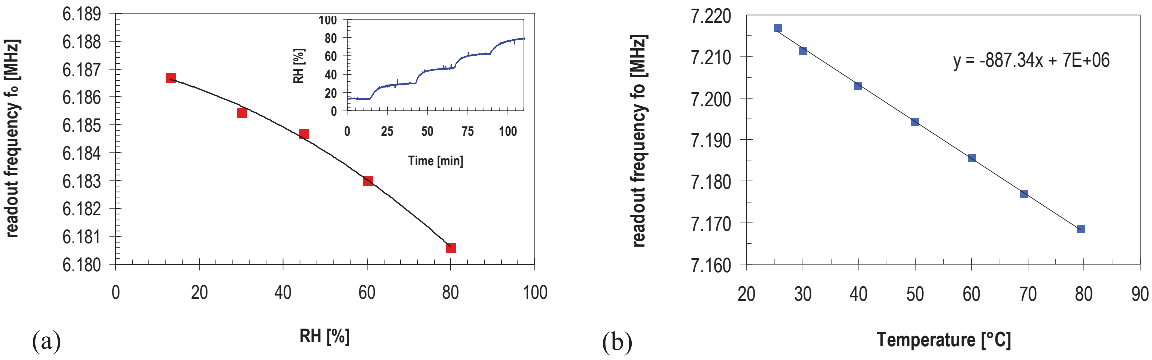

Fig. 5. Measured output frequency of the contactless interrogation system for two RPL sensors: (a) sensor coated with PVP exposed to variable RH; (b) uncoated sensor exposed to variable temperature.

4. Energy harvesting from vibrations and motion

The piezoelectric effect in PZT can be used to harvest energy and convert it from the mechanical to the electrical domain to power autonomous sensors. Widespread energy sources are vibrations and motion. Recent trends in energy harvesting from vibrations are aimed at obtaining broadband response overcoming the bandwidth limitations of the conventional harvesters based on single resonant converters [7]. Best harvesting effectiveness is when the converter operates at resonance, but this cannot be easily ensured with frequency-varying vibrations and is considerably sub-optimal for wideband noise. Broadening the converter bandwidth by reducing its quality factor worsens the peak response.

One viable approach are multi-element harvesters which combine the outputs from multiple converters with different frequency responses into a multi-frequency converter array (MFCA) [8]. In Fig.6a a schematic diagram and prototype of a three-element MFCA are represented. The array is formed by three bimorph cantilevers where PZT thick films have been screen printed on the top and bottom faces of steel shims starting from a low-curing-temperature ink, as described in Section 2. Different tip masses of each cantilever determine the different resonant frequencies shown in Fig.6b where the open-circuit output voltages of the converters under a vertical acceleration of 1 g are reported. The converters have a capacitance and parallel resistance at 100 Hz of 400 pF and 20 MΩ, respectively.

A MFCA has been implemented in a MEMS cantilever array with interdigitated electrodes to exploit the d_{33} mode of a PZT thick film screen printed on the cantilever top surface using a dilute ink, as shown in Fig.7a. At the clamped edge, polysilicon piezoresistors are placed and used to detect the deflection of the cantilevers during testing. Fig.7b shows the open-circuit output voltage of a converter after impulse excitation, compared with the amplified piezoresistor signal taken as a reference. A peak output voltage of about 10 mV results from the PZT film with a thickness in the order of 10 μm.

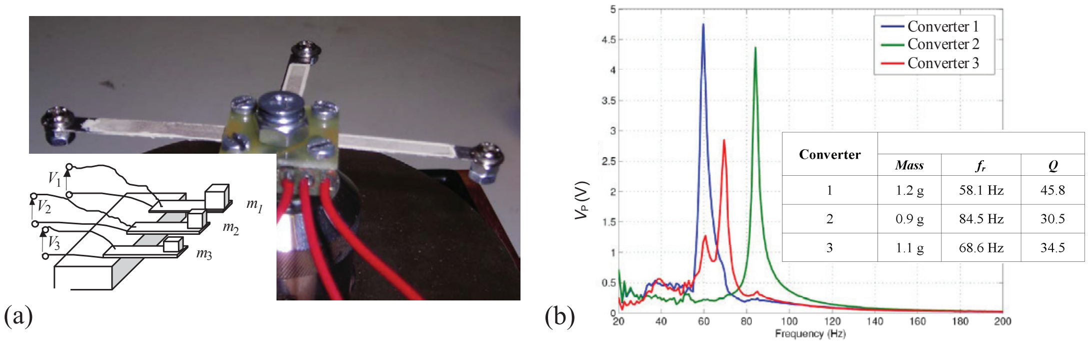

Fig. 6. Multifrequency converter array (MFCA): (a) principle and prototype; (b) Frequency response under sinusoidal excitation.

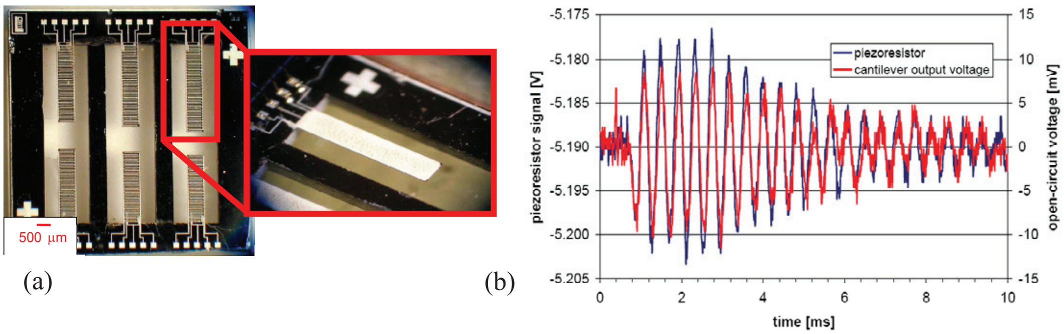

Fig. 7. MEMS implementation of a MFCA: (a) screen printed PZT film; (b) piezoresistor signal and converter output voltage.

Another approach to widen the effective frequency range of the harvested energy from broadband vibrations is the exploitation of nonlinear effects coupled to a piezoelectric converter [9].

An investigated configuration using two permanent magnets is shown in Fig.8a. The magnets introduce a counter-restoring force which sums to the elasticity of the beam and, depending on the distance *d*, causes nonlinearity or bistability [10]. A bimorph cantilever with PZT thick films similar to those of Fig.6 equipped with magnets has been tested under excitation by a band-pass filtered white-noise acceleration.

The open-circuit output voltage from the converter has been measured at different values of the distance *d*. Decreasing the distance the system initially remains monostable and quasi linear, and subsequently the onset of bistability occurs. In this condition, as shown in Fig.8b, the cantilever rapidly jumps between two stable states with a corresponding significant increase in the generated voltage over the linear case at parity of input excitation.

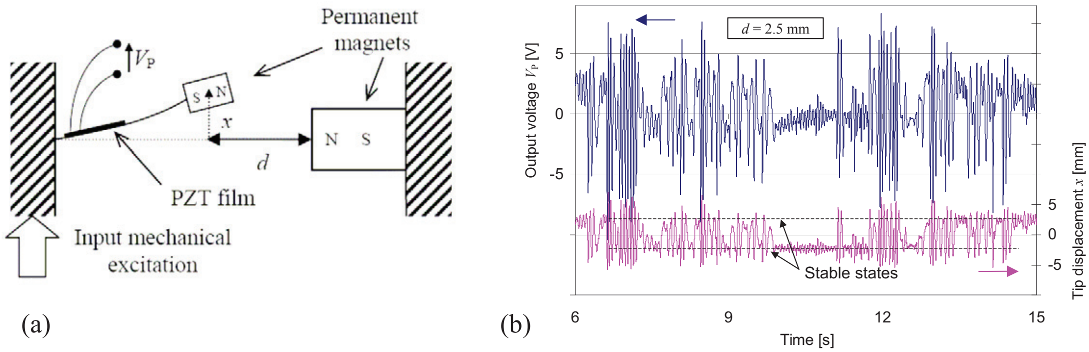

Fig. 8. Nonlinear piezoelectric energy harevester from vibration: (a) structure; (b) displacement and output voltage under bistable behaviour.

When energy has to be harvested from low-frequency motion it can be difficult to efficiently couple it to suitably small converters because of frequency mismatch. A possible approach is to transform low-frequncy motion into a sequence of quasi impulsive excitations leading to a mechanical frequency up-conversion [7]. The concept has been investigated in order to harvest energy from rotation using a fixed piezoelectric converter. The steel cantilever with PZT thick film of Fig.1 has been mounted in the set up of Fig.9a. Two magnets placed on a rotor generate impulse excitation to the ferromagnetic substrate and, in turn, a voltage transient is produced by the PZT film almost independently of the rotating speed.

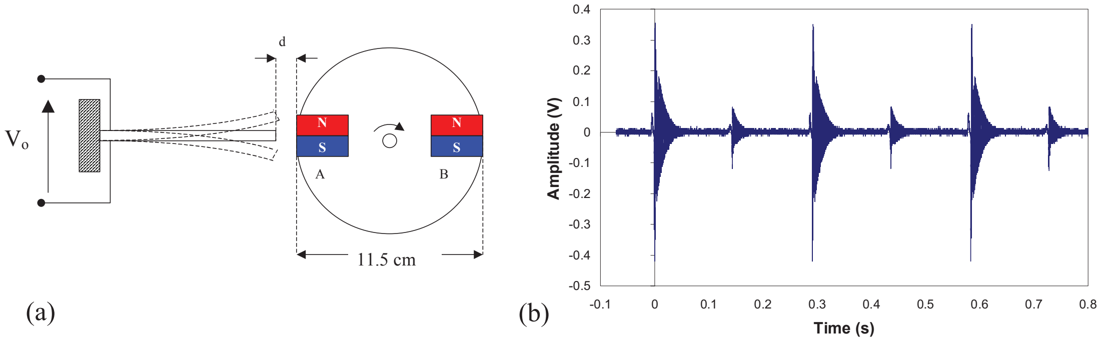

Fig. 9. . Piezoelectric energy harevester from rotational motion based on impulse excitation: (a) structure; (b) and output voltage from the cantilever of Fig.1 for $d = 2$ mm at a rotating speed of about 3 rps.

5. Conclusions

Piezoelectric thick films based on lead zirconate titanate (PZT) have been deposited by screen printing and direct writing techniques on different substrates. Low-curing-temperature ink formulations have been tested to avoid high-temperature firing of the standard pastes, thereby allowing deposition on metal shims and silicon MEMS. At present, the piezoelectric performances of the obtained films are significantly poorer than those of the films obtained from standard TFT PZT pastes, with a d_{33} lower than 10 pC/N.

Passive sensors made by resonant-piezo layers of PZT on alumina with contactless readout by means of air-coupled coils and a tailored gated-interrogation technique have been experimentally demonstrated by sensing humidity, via mass variations, and temperature. Piezoelectric energy harvesters from broadband vibrations based on multifrequency converter arrays and nonlinear structures that exploit PZT thick films on steel members have been described. Early experimental results are reported on energy harvesting from rotational motion based on frequency up-conversion in a PZT-on-steel cantilever contactless actuated by magnets.

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