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Magnetically induced oscillations on a conductive cantilever for resonant microsensors

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Abstract

In some specific applications, the measuring environment can have characteristics unsuitable for the correct working of the electronics, because it is not possible to connect the sensitive element to the conditioning electronics by standard cables or by a radiofrequency link. A possible solution can be a contact-less activation of a passive sensor through a magnetic field. The technique proposed here can be applied to resonant microsensors obtained through a microelectromechanical-system (MEMS) technology based, for example, on a standard CMOS process without any magnetic layers required. A conductive and non-magnetic cantilever, located in a time-variable magnetic field, is brought into resonance thanks to the interaction between the eddy currents in the cantilever and the external magnetic field. In order to test this effect for resonant sensors, an experimental set-up has been built. A piezoelectric bimorph covered by two aluminium sheets is used as cantilever: the aluminium sheets are conductive and non-magnetic layers, while the piezoelectric is only used to detect the induced vibrations. Experimental results demonstrate that, when the time-variable magnetic field is applied, resonant vibrations are induced and measured by the piezoelectric cantilever.

Keywords: Resonant sensors; Magnetic activation; Autonomous sensors

1. Introduction

In these last years, specific applications require the measurement of physical or chemical quantities into environments that are hostile to the electronics. Common examples can be:

- measurement in environments at high temperatures,
- measurement into environment that is not accessible like hermetic boxes or others,
- measurement inside human body,
- measurement on rotating systems.

A possible solution can be the separation of the sensitive element from the conditioning electronics: consequently the sensitive element can work in an environment different from that of the electronics. In this case anyway, the energy required to power the sensitive element is not always available and a possible choice of the sensitive element can be an oscillating structure brought into oscillation by an external activation. The basic principle becomes the measurement of the resonance frequency shift induced by the physical or chemical quantity.

MEMS devices are the object of interest in several branches of science and industry [1] due to the possible low production cost. MEMS sensors based on change of resonance are widely adopted [2,3] to measure different types of physical and chemical quantities. Resonant sensors can be brought into resonance by exciting the mechanical structure using different actuating techniques: electrostatic, magnetic, thermal and piezoelectric [4–7]. Magnetic actuation can be usually obtained by two different techniques, both using an external magnetic field: by exploiting the Lorentz force or by depositing a magnetic film on the resonant structure. An example of the first technique is reported in [8] where a resonant silicon cantilever for force measurement is described: the cantilever is placed in a magnetic field and a current is applied by an independent source.

Magnetic actuation can be also obtained by depositing a magnetic film on the resonant structure. These films are used in a

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lot of resonant sensors and actuators [4]. A magnetic actuation example, which uses a magnetic film, is reported in [5]: the actuator is a cantilever beam that supports an electroplated permalloy film. In this case a power supply is not necessary, but the integration of magnetic films is hardly compatible with standard CMOS process because [8]:

- There is the possibility of spreading some elements of the magnetic layer into the silicon and degrading the circuits either during their deposition or subsequent processing.
- Magnetic films are often deposited at elevated temperatures to obtain optimized properties, but generally high temperatures cause stresses in the structure and problems with aluminium metallization.
- Magnetic films, deposited on silicon chip, can have adhesion problems.

A lot of examples where micromachining technologies can be coupled with standard CMOS technology are reported in literature: sacrificial layer and other deposition process are some examples [9,10]. Thus, suspended structures, membranes or bridges can be realized on the same integrated circuit with very low damages to the electronic parts by sacrificial layer or by opportune etching processes coupled with protective layer.

In this paper a magnetic-contactless activation of a cantilever, with a conductive and non-magnetic film on it, is described. The resonant element is passive and does not require internal power supply. Moreover the technique proposed here can be applied to resonant microsensors obtained through a MEMS technology based on a standard CMOS process.

2. Operating principle

As shown in Fig. 1, a conductive cantilever (whose left side face is in the $z=0$ plane) is located in a static and in a time-changing magnetic flux field [11–13]: the time changing (B_0) and the static (B_1) fields have both transverse (B_{1z}, B_{0z}) and in plane ($B_{1\mathrm{p}}, B_{0\mathrm{p}}$) components. The transverse time-changing magnetic field generates eddy currents in the cantilever; the external dynamic and static magnetic fields (B_0 and B_1) and the induced currents in the cantilever are then responsible for electromagnetic forces acting on the cantilever. These forces are investigated in order to exploit their possible use in a resonant sensor.

Neglecting displacement currents, the relation between transverse magnetic fields (H_z) and in plane eddy currents and electric fields (E_p) is governed by Maxwell equations:

$$\nabla \times E_\mathrm{p} = -\frac{\partial B_z}{\partial t} = -\left(\frac{\partial B_{0z}}{\partial t} + \frac{\partial B_{\mathrm{e}z}}{\partial t}\right) \qquad (1)$$

$$\nabla \times H_{\mathrm{e}z} = J_{\mathrm{ep}} = \sigma E_\mathrm{p} \qquad (2)$$

$$B_z = \mu_0 H_z = \mu_0 (H_{0z} + H_{\mathrm{e}z}) \qquad (3)$$

where $B_{\mathrm{e}z}$ is the (transverse) magnetic flux induced by the (in plane) eddy currents (whose density is J_{ep}) and σ is the electric conductivity of the beam. Applying the curl operator to Eq. (2), in the limit of very small conductive sheet thickness (h), we get the following equation for the magnetic field induced by the eddy currents:

$$\nabla^2 H_{\mathrm{e}z} - \mu_0 \sigma \frac{\partial H_{\mathrm{e}z}}{\partial t} = \sigma \frac{\partial B_{0z}}{\partial t} \qquad (4)$$

Solving Eq. (4) we then get the eddy-current distribution by Eq. (2) and the electromagnetic force from Lorentz equation:

$$F = h J_{\mathrm{ep}} (B_0 + B_1 + B_{\mathrm{e}z}) \qquad (5)$$

Note that, due to the mechanical constraint (the dark region of the cantilever in Fig. 1), transverse magnetic flux field components are responsible for longitudinal and lateral strain of the beam, while in plane components exert a torque, as shown in Fig. 1. In sinusoidal regime at angular frequency ω, Eq. (5) becomes:

$$F \cong k_0 + k_1\, \mathrm{e}^{\mathrm{j}\omega t} + k_2\, \mathrm{e}^{\mathrm{j}2\omega t} \qquad (6)$$

where k_0, k_1 and k_2 are suitable complex constants.

From Eq. (6) we expected that, generating a magnetic field consisting of a static and dynamic component, the forces on the cantilever have at lest two sinusoidal components: one at frequency f and the second at $2f$.

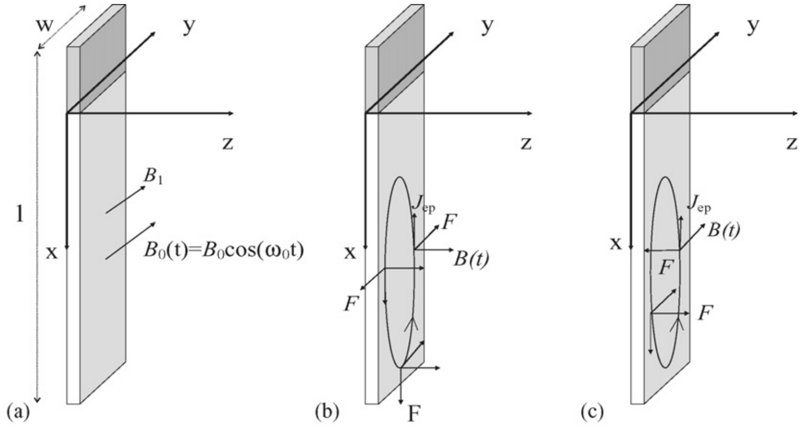

Fig. 1. Schematic drawing of the conductive cantilever (15 mm × 1.5 mm × 0.6 mm) in a time-changing magnetic field: general case (a), with only transverse (b), or in plane components (c). The dark region represents the mechanical constraint.

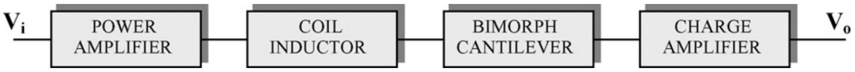

Fig. 2. Block scheme of the experimental system.

The forces applied to the cantilever generate movement of the cantilever at the frequencies *f* and 2*f*.

3. Experimental system

A block diagram of the experimental system is reported in Fig. 2, it consists of a sinusoidal generator, followed by a power amplifier that drives a coil inductor working as a magnetic field generator. This magnetic field acts on the conductive cantilever bringing it into oscillations. Because the cantilever is a piezoelectric transducer, the oscillations are revealed by a charge amplifier, whose input is at the piezoelectric element output.

The power amplifier drives the coil with a voltage up to ±30 V with a maximum current of 5 A and its bandwidth is about 100 kHz. The inductance coil consists of a ferrite core (N27) "C" shaped over which a 1000 turns are wound. The inductance value is around 45 mH. The inductance core presents also a static flux field due to a residual magnetization that has been measured by inserting a magneto-resistive sensor into the air gap. The time-changing magnetic field is around 600 A/m near the cantilever, while the static, due to residual magnetization, is around 1 kA/m.

The piezoelectric bimorph cantilever is a RS-285-784 and has a piezoelectric constant g_{31} of 12.1×10^4 Vm/N. Two aluminium sheets (approximate thickness of 20 μm) have been glued on the two sides of the bimorph. First the aluminium sheets have been cut (the same size of the bimorph, 15 mm × 1.5 mm) with the aid of an optical microscope. Then they have been strewed with cyanoacrylate glue, and pressed on the bimorph by tweezers. Also a cantilever with only one sheet has been tested but two aluminium sheets have been found to produce a higher signal. Aluminium has conductivity σ of $37.7 \times 10^6\ \Omega\,\mathrm{m}^{-1}$ and it is a non-magnetic material. As sketched in Fig. 1, the cantilever is clamped in one extremity, with a mechanical constraint that should be as rigid as possible. In this experimental apparatus, a screw and a Plexiglas block are used to firmly clamp one extremity of the cantilever. The screw has been obtained with an epossidic resin which, becoming harder, holds the cantilever. In Fig. 3 a photo and a schematic drawing are reported: the bimorph is clamped to the fixed support and the conductive part is put into the air gap of the inductor core. All the support is fixed at an antivibration breadboard.

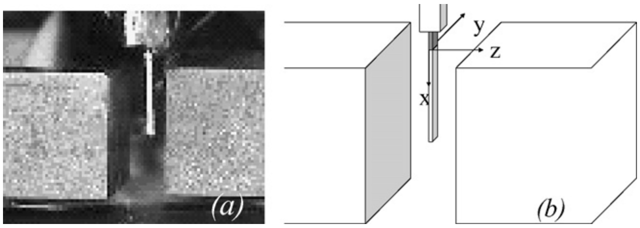

Fig. 3. A picture of the experimental set-up (a) and its schematic drawing (b).

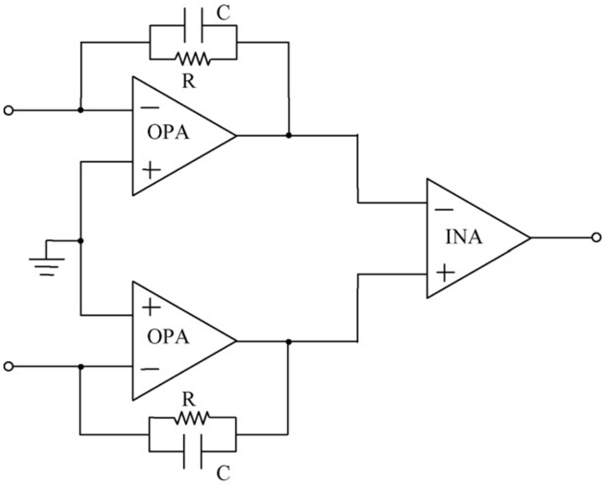

Fig. 4. The charge-amplifier circuit, where $R = 15\ \mathrm{M}\Omega$ and $C = 68$ pF.

The charge amplifier has a differential input stage and an instrumentation amplifier as output stage. The two operational amplifiers are OPA637. The instrumentation amplifier is INA118; it has a gain of 5 and a bandwidth of 100 kHz (Fig. 4).

Most experiments have been executed by using a network analyzer to generate a sinusoidal input at frequency *f* and analyze the displacement induced by the first harmonic at frequency *f*. Moreover other experiments have been conducted by driving the power amplifier with a sinusoid at the frequency generated by function generator and measuring the charge amplifier output with a spectrum analyzer to verify the presence of a displacement induced by the first and second harmonics of the force according to Eq. (6).

4. Experimental results

The system has been driven by the network analyzer scanning the frequency over a known range looking for a resonance condition. In Fig. 5 the frequency response of the system (V_o/V_i) is reported: a point is clearly visible, located at 2320 Hz that denotes a resonance frequency. To verify that such frequency is the mechanical resonance f_m, the same resonance has been determined through a different method. The impedance of the piezoelectric cantilever has been measured and the maximum value of the real part of its admittance corresponds to 2320 Hz.

To modify the mechanical resonance frequency, the cantilever mass has been changed by charging the tip of the same cantilever with a minute drop of paint. In particular two drops, each of different mass, have been deposited one after the other obtaining three different experimental situations that, in the following, are referred as: (1) no drop; (2) one drop; (3) two drops.

The impedance of the cantilever has been measured by an impedance analyzer, and three different diagrams corresponding to the previous defined three cases are shown in Fig. 6.

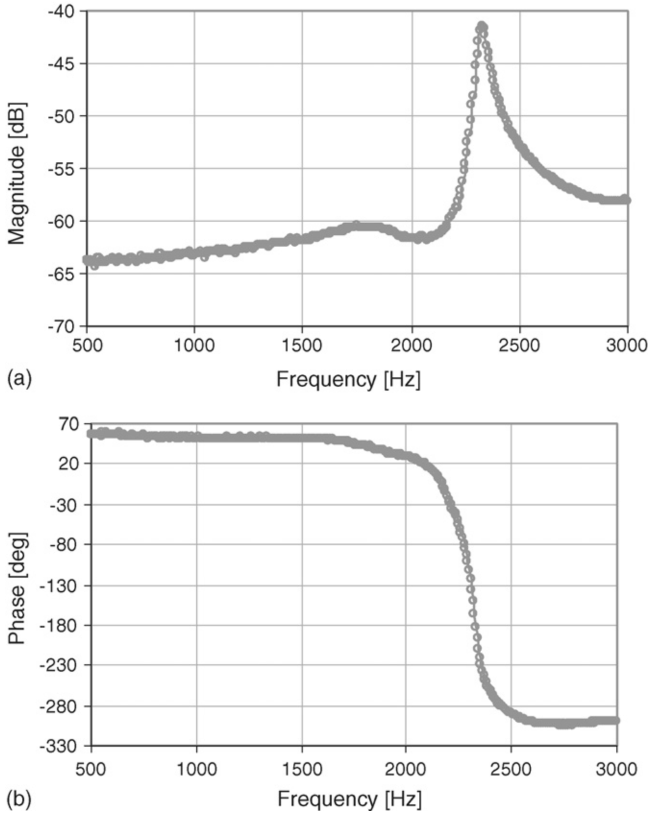

Fig. 5. The magnitude (a) and phase (b) diagrams of the frequency response of the system.

Table 1
Mechanical cantilever resonances

Drops	f_m (Hz)
0	2320
1	2268
2	2090

From the experimental data, the mechanical resonances have been derived (frequency f_m in Table 1).

Fig. 7 shows the experimental frequency response measured with the proposed system when the cantilever is charged with paint drops on its tip. The resonant frequencies, for the loaded cantilever, are lower than the corresponding frequencies of the unloaded cantilever.

According to Eq. (6), if the current driving the coil is a sinusoid at frequency f, the force has at least f and $2f$ components. The coil is driven at frequency f and a spectrum analyzer measures the charge amplifier output. Moreover also the spectrum of the current driving the coil is measured to exclude the presence of harmonics higher than the fundamental.

The frequency f of the current driving the coil has been set to $(1/2)f_m$. When no mass is charged over the cantilever ("no drop" case) the input and output spectrum diagrams are reported in Fig. 8.

While the input clearly has only its fundamental, the output spectrum shows two peaks (indicated by arrows): the first placed at frequency f and the second with a very high magnitude

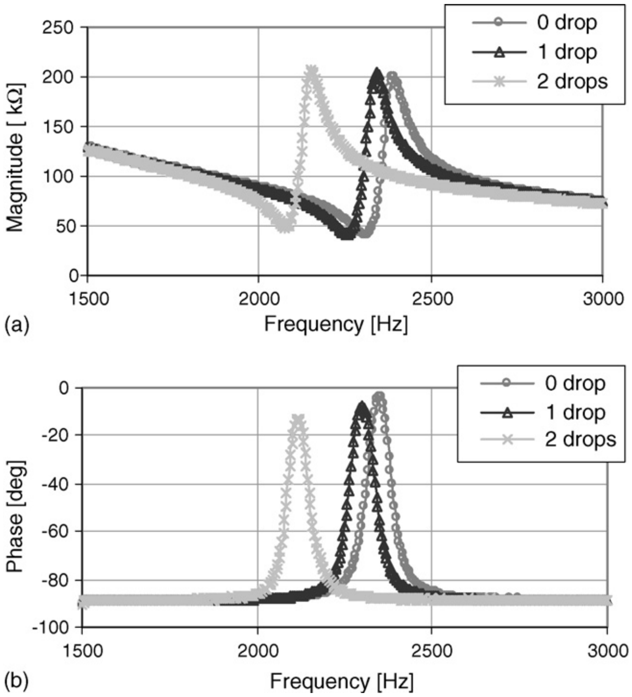

Fig. 6. The impedance magnitude (a) and phase (b) of the cantilever.

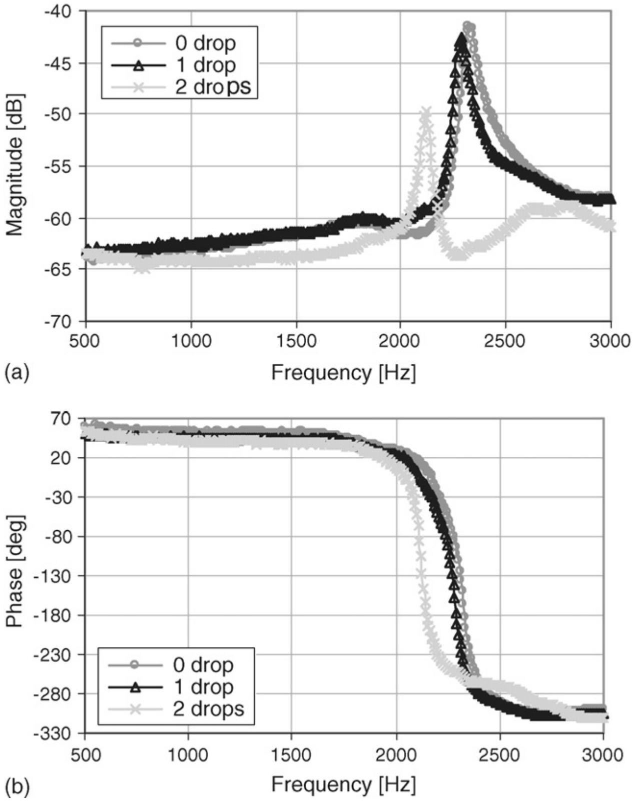

Fig. 7. The magnitude (a) and phase (b) diagrams of the signals at different mass quantities.

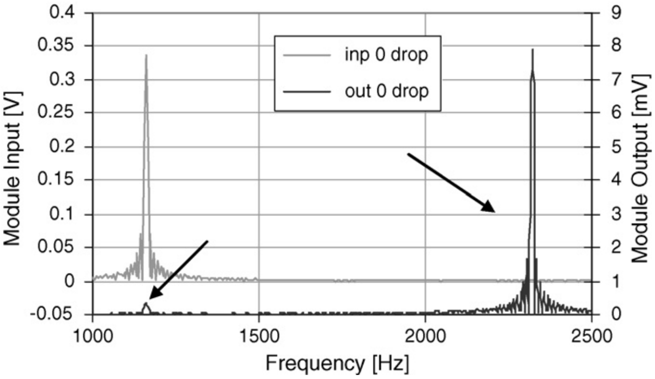

Fig. 8. The input and output spectrum diagrams calculated at zero mass, with the input-signal frequency of (1/2)f_m ((1/2)2300 Hz = 1150 Hz).

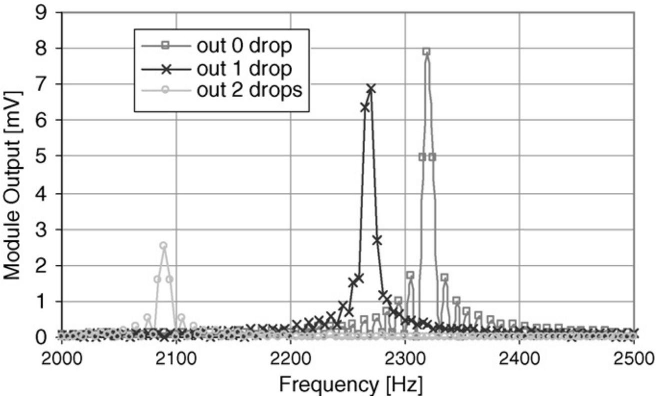

Fig. 9. The output spectrum diagrams with the input at (1/2)f_m and different mass loads.

at frequency f_m. When the paint drops are deposited onto the cantilever ("one drop" and "two drops" cases), a similar behavior has been observed. Fig. 9 shows the output spectra in a small frequency window, for the three cases, each driven at its (1/2)f_m. As it can be seen the resonance frequency value and the vibration amplitude (proportional to the magnitude of the output voltage) decrease with the increase of the mass on the cantilever.

In order to exclude that the resonance can be induced by external mechanical noise and that the magnetic field generates oscillation on the cantilever at a specified frequency, the coil is driven by a sinusoid whose frequency is not equal to the mechanical resonance and its sub-harmonic frequencies. In Fig. 10 the input is a sinusoid at 350 Hz. The output diagram shows two peaks: first at 350 Hz and another at double frequency 700 Hz. Comparing the amplitude of the oscillation induced at resonance, as reported in Fig. 8, in this case the value is lower being the scale of the output magnitude one order of magnitude below. Even if the frequency range analyzed is broad enough to contain the value of the resonance frequency, which in the case of two drops is located at 2090 Hz according to Table 1, no significant components at this frequency is present.

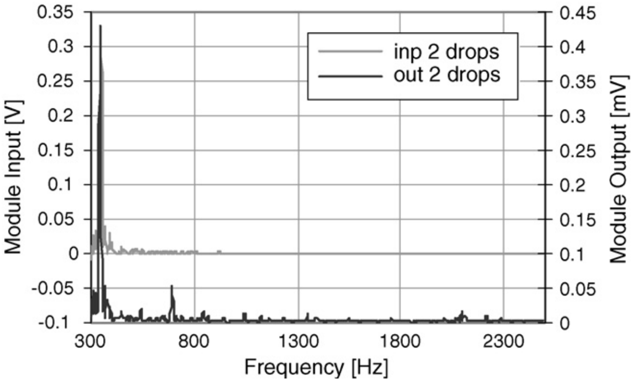

Fig. 10. The input and its output spectrum diagram of the signal at sub-harmonic frequency.

5. Conclusions

In this paper the possibility to induce vibrations and resonance on a conductive and non-magnetic cantilever by a time-changing magnetic field has been discussed. Using a piezoelectric cantilever we have proved that the induced resonance is mechanical; the method has been experimentally demonstrated. The force acting on the cantilever arises from the interaction between the eddy current, induced in the conductive cantilever by the time-changing magnetic field, and the magnetic field itself. It is expected that the proposed technique could be used for development of resonant micro sensors in MEMS technology based on a standard CMOS process coupled with conductive and non-magnetic layers.

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Biographies

Costantino De Angelis was born in Padova, Italy, in 1964. He received the Laurea degree (cum laude) in electronic engineering and the PhD degree in telecommunications from the University of Padova, Padova, Italy, in 1989 and 1993, respectively. From 1993 to 1994 he was with the Department of Mathematics and Statistics of the University of New Mexico at Albuquerque, USA. From 1995 to 1997 he was assistant professor at the Department of Electronics and Informatics of the University of Padova, Italy. From 1997 to 1998 he was with IRCOM ("Institut de Recherche en Communications Optiques et Microondes") at the University of Limoges, France. Since 1998 he is professor of electromagnetic fields at the University of Brescia, Brescia, Italy. His fields of technical interest are optical communications, soliton propagation, and photonics. He has authored or coauthored 160 among papers and conference contributions.

Vittorio Ferrari was born in Milan, Italy, in 1962. In 1988 he obtained the Laurea degree in physics cum laude at the University of Milan. In 1993 he received the research doctorate degree in electronic instrumentation at the University of Brescia. He is currently an associate professor of electrical and electronic measurements at the Faculty of Engineering of the University of Brescia. His research activity is in the field of sensors and the related signal-conditioning electronic circuitry. Particular topics of interest are acoustic-wave piezoelectric sensors, microresonant sensors and MEMS, autonomous sensors and power scavenging, oscillators for resonant sensors and frequency–output interface circuits. He is involved in national and international research programmes, and in projects in cooperation with industries.

Daniele Marioli was born in 21 January 1946, in Brescia. In 1969 he graduated in electrical engineering at Pavia University and since then he has been practicing research and educational activities at Polytechnic of Milano and at the Brescia University, where he has been working since 1990 as full professor in electronics. Besides he was chief of the Automation Electronics Department. The research field of Prof. Marioli is the design, realization and test of sensors, electronic instrumentation and signal processing electronic circuits. The activities in these fields are related to the realization of innovative sensors in thick film technology, based on piezoelectric, piroelectric and piezoresistive behaviors of screen printable pastes, and in MEMS technology, for the detection of physical quantities (acceleration, force, pressure, mass, etc.); the realization of high resolution electronic instrumentation for capacitive measurements; the design and realization of integrated electronic circuit as front-end of piezoresistive based sensors; development of new linearization techniques based on neural networks; development of web-sensors and wireless-sensors. He is author and coauthor of more then 200 scientific papers published on international and national journals and conference proceedings and co-inventor of four patents.

Emilio Sardini was born in Commessaggio, Mantova, Italy in 1958. He graduated in electronic engineering at the Politecnico of Milan, Italy, in 1983. Since 1984 he joined the Department of Electronic of Industrial Automation of the University of Brescia, Italy. From 1986 to 1998 he has been an assistant professor. Since 1998 he is an associate professor in electrical and electronics measurements and recently won a full professor position. He teaches courses in the field of electronics instrumentation. His research activity has been addressed to sensors and electronic instrumentation, in particular to the conditioning electronics mainly of capacitive and inductive sensors, microprocessor based instrumentation, development of thick film sensors, instrumentation for noise and for low frequency acceleration measurements.

Mauro Serpelloni was born in Brescia, Italy, in 1979. He received the Laurea degree summa cum laude in industrial management engineering from the University of Brescia in October 2003. Since November 2003 he has been a PhD student in electronic instrumentation at the University of Brescia, Department of Electronics for Automation. He has worked on several projects relating to design, modeling and fabrication of measurement systems for industrial applications. His research interests include especially contactless transmissions between sensors and electronics, contactless activation for resonant sensors and signal processing for microelectromechanical-systems.

Andrea Taroni was born in 1942. He received his degree in physical science from the University of Bologna, Italy, in 1966. He was an associate professor at the University of Modena from 1971 to 1986. Since 1986 he has been full professor of electrical measurements at the University of Brescia, Italy. He has done extensive research in the field of sensors for physical quantities and electronic instrumentation, both developing original devices and practical applications. He is author of more than 100 scientific papers.