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Distortion-free measurement of electric field strength with a MEMS sensor

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Abstract

Small-scale and distortion-free measurement of electric fields is crucial for applications such as surveying atmospheric electrostatic fields, lightning research, and safeguarding areas close to high-voltage power lines. A variety of measurement systems exist, the most common of which are field mills, which work by picking up the differential voltage of the measurement electrodes while periodically shielding them with a grounded electrode. However, all current approaches are either bulky, suffer from a strong temperature dependency, or severely distort the electric field requiring a well-defined surrounding and complex calibration procedures. Here we show that microelectromechanical system (MEMS) devices can be used to measure electric field strength without significant field distortion. The purely passive MEMS devices exploit the effect of electrostatic induction, which is used to generate internal forces that are converted into an optically tracked mechanical displacement of a spring-suspended seismic mass. The devices exhibit resolutions on the order of $100 \text{ (V/m)} / \sqrt{\text{Hz}}$ with a measurement range of up to tens of kilovolt per metre in the quasi-static regime ($\lesssim 300 \text{ Hz}$). We also show that it should be possible to achieve resolutions of around $\sim 1 \text{ (V/m)} / \sqrt{\text{Hz}}$ by fine-tuning of the sensor embodiment. These MEMS devices are compact and could easily be mass produced for wide application.

It is difficult to measure electric field strength without interference by the measuring instrument. Dielectric bodies develop surface charges which usually lead to moderate distortions of the field, while large, electrically conducting bodies generate significant field distortions in their proximity. This problem becomes even more serious, if parts of a sensor

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Author contributions

A.K., H.S., and W.H. carried out the design, modelling, and measurements. J.S. and A.J. were responsible for the manufacturing of the device, while, F.K., M.S. and F.K. supported the measurements and the design of the devices. R.B. supported in modelling and was involved in acquiring funding for the work. All authors contributed to the manuscript.

Competing financial interest statement

The Authors have no competing interests as defined by Nature Publishing Group, or other interests that might be perceived to influence the results and/or discussion reported in this article.

Data Availability Statement

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

have to be grounded or connected to large conductors in order to establish a reference potential. Current measurement systems for static and low-frequency electric field can be divided into two general categories: direct electrical conversion comprising double probes of electrical potential as well as field mills [1, 2] and electrooptical systems [3, 4]. A variety of alternative approaches also exist [5, 6] but they all suffer from drawbacks like limited lifetime or scaleability. Double probes can achieve resolutions of about $0.1(\mu\text{V}/\text{m})/\sqrt{\text{Hz}}$ [7], but such highlights rely on a diluted plasma environment, precisely shaped probe electrodes exhibiting low work function surfaces, and probe inter-distances of several metres. As the potential probes are usually active devices, carefully designed, actively shielded booms are required to ensure moderate distortion of the field to be measured. The conventional system for measuring low-frequency electric fields is the field mill with a typical resolution of about $50(\text{V}/\text{m})/\sqrt{\text{Hz}}$ [8]; for comparison, the fair-weather electric field at ground level is $\sim 100 \text{ V/m}$ and fields inside thunderclouds can be as high as 50 kV/m [9, 10]. Field mill measurements are, however, inherently error-prone and strongly depend on the immediate environment. Conventional field mills are also relatively bulky [11]. Consequently, there have been attempts to miniaturise this concept with MEMS technology [12, 13], which allows mass-production of low-cost, small-size devices. However, these approaches still require grounded parts, which usually leads to distortions. In this context, electrooptical systems are superior, since they rely on specific dielectrics and do not require grounded connections [14]. Electrooptical crystals can be used to quantify the strength of the electrical field either through absorption of light or by changes in the refractive index [15, 16, 17]. Optical sensors based on the Pockels effect have been widely studied in various arrangements and offer typical resolutions of $0.6(\text{V}/\text{m})/\sqrt{\text{Hz}}$ [18, 19, 20, 3]. But such electrooptical electric field sensors suffer from an intrinsic temperature instability due to the pyroelectric effect and the thermal expansion of the material [21], and no optical sensor has so far satisfyingly solved this problem [22, 4].

Transduction scheme

Our approach to electric field sensing overcomes the mentioned issues by relying on the effect of electrostatic induction. This effect is a consequence of the mobility of free charge carriers in conducting solids. If a conductor is placed in an electrical field $\mathbf{E}$, the free charge carriers inside the conductor redistribute in contrast to lattice-bound opposite charges. This polarisation compensates $\mathbf{E}$ inside the body. Thus, oppositely charged regions develop at the conductor's surface. Each of these surface regions experiences an outward bound force due to the $\mathbf{E}$ -field while the total force on the body remains zero. If one separates these oppositely charged regions keeping the only connection in between in the form of a conducting spring, one can observe an elongation of the spring due to the electric field (see Fig. 1a and b). This is due to the electrostatic force pulling on the individual charged surfaces and the conductivity of the spring by which the polarisation of the body is maintained. In the case of a conducting sphere (radius R) inside a uniform field $\mathbf{E} = E_0 \mathbf{e}_z$ pointing in z -direction ($\mathbf{e}_z$ being the unit vector in z -direction), the total electrostatic force experienced by, e.g., the right half of the full sphere, i.e. the positively charged region, can be calculated analytically [23] and equals

$$\mathbf{F}_{\text{es}} = F_{\text{es}} \mathbf{e}_z, \quad F_{\text{es}} = \frac{9}{4} \pi R^2 \varepsilon_0 E_0^2 = a_s \varepsilon_0 E_0^2, \quad (1)$$

where $a_s = 9\pi R^2/4$ takes into account the highly symmetric geometry of the sphere and ε_0 is the vacuum permittivity. The left half of the sphere experiences an equally strong force which points in the opposite direction. Thus, the total force on the sphere equals zero. For less symmetric shapes, the geometric prefactor a_s has to be replaced by a tensor with components a_{ij} and Eq. (1) would then read in index notation $F_{\text{es},i} = a_{ij} \varepsilon_0 E_0 E_{0,j}$ (see Supplementary Figure 2). In basic sensor operation, the x -component of $\mathbf{F}_{\text{es}}$ is converted to a relative displacement δx of the spring-suspended MEMS part of the structure. Owing to the linear elastic material behaviour of the suspending springs combined with the small achievable deflections, this force-deflection conversion can be modelled by a lumped parameter approach (mass m , stiffness k , and damping parameter d) utilizing linear system theory. Accordingly, we have shown that the mechanical system can be described by a harmonic oscillator with low-pass characteristic and transfer function

$$\tilde{H}(\omega) = \frac{1}{m(\omega_0^2 - \omega^2 + 2i\gamma\omega)} \quad (2)$$

with $i = \sqrt{-1}$, where the tilde symbol indicates frequency domain representation and ω denotes the angular frequency of the force excitation. The resonance frequency $\omega_0 = \sqrt{k/m}$ and the decay parameter $\gamma = d/(2m)$ in Eq. (2) define the spectral properties of the transduction entirely. The system response of the force-deflection conversion is governed by $\tilde{X} = \tilde{H} \cdot \tilde{F}_{\text{es}}$. The quadratic dependence of $\mathbf{F}_{\text{es}}$ on E in Eq. (1) imposes, however, a non-linear conversion between force and electric field that involves a convolution $\tilde{X} \propto \tilde{H} \cdot (\tilde{E} * \tilde{E})$ in the spectral domain. From this fundamental relationship we can conclude that a unique back-calculation from the measured deflection to the unknown electric field $\tilde{E}(\omega)$ is only possible if its upper cut-off frequency is smaller than half of the cut-off frequency of the mechanical system $\tilde{H}(\omega)$. In the remainder of this paper, the special case of a time-harmonic electric field will be studied intensively. For this time-harmonic electric field $E(t) = \hat{E}_0 \cos(\omega t)$, the general theory simplifies to an actuating force $F_{\text{es}} \propto E_0^2 \cos^2(\omega t) = E_0^2 (1 + \cos(2\omega t))/2$ consisting of an AC-component with twice the frequency of the electric field (i.e., a ω to 2ω conversion from electric field to force) and a DC-component.

The displacement of the spring-suspended Si part is read out optically by detecting the light flux modulated by the device [24, 25]. This is achieved by an optical shutter which is composed of a stationary (patterned by Cr deposited on glass) and a moveable aperture array (etched into Si, displaced by F_{es}) of rectangular holes placed on top of each other (see Fig. 2a). Each of the grids bears a large number of $N_h = 147 \times 22 = 3234$ holes with width $w_h = 10 \mu\text{m}$ and length $l_h = 100 \mu\text{m}$ that are, in the resting position, shifted by $w_h/2$ with respect to each other. When the moveable part is displaced, the transmitted light flux changes

according to the shading. The corresponding area change is given by $\delta A_{\text{open}} = N_h l_h \delta x$. Thus, the overall intrinsic displacement sensitivity $S_d \propto N_h l_h$ is determined by the number of holes. The transfer characteristic of the transducer is, therefore, given as

$A(\omega) = S_d F_{\text{es}} / m(\omega_0^2 - \omega^2 + 2i\gamma\omega) = S_{\text{es}} E_0^2 / (\omega_0^2 - \omega^2 + 2i\gamma\omega)$ with the electromechanic sensitivity $S_{\text{es}} := S_d a \epsilon_0 / m$ in units of $(\text{V}/\text{s}^2) / (\text{V}/\text{m})^2$ and a being the corresponding geometric prefactor of the electrostatic force. Furthermore, it should be stressed that the optical readout makes the presented MEMS E-field transducer an entirely passive component: In contrast to all field mills, the mechanical actuation is solely caused by the E-field to be measured. If glass fibres are used to guide the light to and from the MEMS, the E-field can be measured at a remote location ensuring minimal perturbations of the field. Note that in contrast to interferometric readouts, it is not necessary to use a coherent light source. Recently, even the Earth tides were measured with a similar readout [26].

MEMS implementation

In order to transfer the described concept into a silicon microstructure, there were two straightforward solutions (Fig. 2b), a bare structure consisting of only one Si domain, and a semi-covered structure having a second Si domain separated from the moving part by a relatively narrow gap. While the former poses the more direct implementation of the principle depicted in Fig. 1b, the latter is the more effective one. The additional silicon part (domain B) itself is subject to the electrostatic induction and, hence, concentrates the electric field inside the gap. This increases the force experienced by the moving silicon part. We found that for gap widths $x_r \lesssim 200 \mu\text{m}$, F_{es} is proportional to x_r^{-1} (see Methods). Therefore, we opted for the semi-covered structure and the MEMS design as depicted in Fig. 2c and d. The flexible suspensions for the moving shutter were designed in U-shape instead of straight beams to evade mechanical non-linearities which usually occur at larger deflections. The silicon parts of the MEMS were fabricated with silicon on insulator (SOI) technology on wafer-level scale. The stationary shutter was patterned onto a glass wafer which was then bonded to the SOI wafer using a photoresist (SU-8) as bonding promoter (Fig. 2c). After bonding, the two Si domains were held together by the glass chip and the connection in between was cut away during dicing the wafer into individual chips (for more details see Methods). This separation is necessary, since any remaining connection would shield the moving mass from the field and render the device useless. Four variations of the layout named ChXX were designed, differing in spring stiffness and gap width. The first X in the name corresponds to the stiffness of the structure which was set to $k = 1 \text{ N/m}$ and $k = 2 \text{ N/m}$ denoted by $X = 0$ and $X = 1$, respectively. Thus, the resonance frequencies of the layouts Ch0X and Ch1X should differ by a factor of $\sqrt{2}$. The second X (= 0, 1) denotes the width of the separation gap of $x_r = 10 \mu\text{m}$ and $x_r = 20 \mu\text{m}$, respectively. The corresponding sensitivities should, therefore, differ by a factor of 2 (see Tab. 1). Ten copies of each layout were fabricated.

Characteristics of the MEMS device

The MEMS sensors were characterised in two ways. First, the mechanical properties, i.e. ω_0 , γ and the quality factor $Q = \omega_0 / 2\gamma$, were investigated by recording the frequency

response to inertial excitation by a vibration with constant amplitude. The mechanical characterisation allowed for testing the functionality and determining the mechanical properties of the transducers in a known environment before attempting to measure the electric field (see Methods). In the second step, the MEMS sensors were tested in a time-harmonic electric field. The chips were placed in a well-defined homogeneous AC electric field with amplitudes ranging from 342 V/m up to 21 kV/m and a frequency range from 1 Hz to 2 kHz. Again, the output of the readout circuit was recorded with a lock-in amplifier, only this time at twice the field frequency (compare Fig. 3). However, in a "real world" application, where the electric field is neither sinusoidal nor a priori known, frequency-based measurement techniques like lock-in can still be applied for the measurement of the quasi-stationary electric fields as long as $\tilde{E}$ is bandlimited according to section Transduction scheme. Lock-in amplifiers in frequency sweep operation or spectrum analyzers can then be utilized to acquire the frequency spectrum of the convolution of $\tilde{F} \propto \tilde{E} * \tilde{E}$. Inverse Fourier transform leads to the corresponding temporal evolution of the squared electric field E^2 . Simply applying a square root operation yields the electric field strength E to be determined.

Exemplary results for the frequency response of one test structure of group Ch00 are shown in Fig. 4a. The quadratic behaviour of the transduction can be seen more clearly in Fig. 4b. There, each curve has been fit to the transfer characteristic $U_{\text{out}} \propto A(\omega)$ extracting the values of the electromechanic sensitivity S_{es} . The noise floor of this configuration of roughly 10 μV is determined by the electronic (Johnson) noise of the transimpedance resistor. Considering the quadratic nature of the transduction, this is equivalent to an electric field of roughly 153 V/m. With respect to the equivalent noise bandwidth of $ENBW = 0.78$ Hz of the lock-in amplifier at an off-resonance measurement frequency of 100 Hz, this yields a resolution of $r_{\text{es}} = 173 (\text{V/m}) / \sqrt{\text{Hz}}$.

The measurement equipment limits the electric fields to $\lesssim 21.1$ kV/m. Therefore, we estimate the dynamic range of this device by determining the maximum measurable electric field which causes the maximum allowed deflection of the moving mass. The mechanical deflection is limited by the gap width x_r of 10 μm . However, it is expected that at roughly $x_r/3$ the electrostatic pull-in of the moveable mass takes place [27]. The electric field resulting in a deflection of $x_r/3 = 3.3$ μm follows by taking the actuation voltage corresponding to this deflection and calculating the respective electric field, which results in a maximum measurable field of 98.9 kV/m.

The results of the electromechanic sensitivity S_{es} for all layout groups are listed in Table 1. The values of S_{es} incorporate only the electrostatic force and the intrinsic sensitivity of the device and are, therefore, independent of ω_0 and γ . Thus, groups Ch01 and Ch11, which differ only by their stiffness or ω_0 , are equivalent with respect to S_{es} . They have the same gap $x_r = 20$ μm determining F_{es} and the same optomechanic sensitivity S_d . Combining these groups, one finds $S_{\text{es,ChX1}} = (1.39 \pm 0.36) \cdot 10^{-4} \text{ Vs}^{-2}/(\text{V/m})^2$. The same is true for Ch10 and Ch00 with the same sensitivity S_d but different $x_r = 10$ μm yielding $S_{\text{es,ChX0}} = (2.68 \pm 0.94) \cdot 10^{-4} \text{ Vs}^{-2}/(\text{V/m})^2$. In the case of group Ch11, i.e. the stiffer and less sensitive group, the maximum measurable electric field can be as high as 230 kV/m.

Conclusions

At the moment the achieved field resolution is determined by the electronic noise of the readout circuit. The fundamental limit of the sensor, i.e. the Brownian noise, can be estimated by the mean noise force $F_{th} = \sqrt{4k_B T d}$, where k_B , T , $d = 2m\gamma$ are the Boltzmann constant, the temperature, and the damping coefficient, respectively. Therefore, the equivalent displacement evaluates to $\delta x_{th} = \sqrt{4k_B T / m \omega_0^3 Q} = 0.56 \text{ pm} / \sqrt{\text{Hz}}$ with a motional mass of $m = 6.43 \cdot 10^{-7} \text{ kg}$. The displacement sensitivity for the presented electric field measurement configuration was estimated by tapping on the side of the setup in order to achieve a displacement larger than the width of one hole, i.e. $> 10 \text{ }\mu\text{m}$. In this case the waveform at the photodetector becomes clipped on both sides and the voltage difference between maximum and minimum corresponds to a displacement of $10 \text{ }\mu\text{m}$. The fundamental electric field resolution for the depicted designs would therefore be $r_{es,th} = 40.6 (\text{V/m}) / \sqrt{\text{Hz}}$. Following the results obtained by the FEM simulations, future devices with a resolution of below $1 (\text{V/m}) / \sqrt{\text{Hz}}$ are feasible by reducing the gap width x_r and increasing the number of holes N_h and, thus, the sensitivity S_{es} . This resolution can be reached even without cooling or complex vacuum packaging.

A further benefit of the concept is the temperature influence on the device compared to optical principles based on material effects. Temperature changes slightly affect the Young's modulus of Si of the MEMS part (in the range of 50 ppm/K , [28]) combined with thermal expansions in the range of 2.3 ppm/K affecting mainly spring stiffnesses. Hence, the temperature dependence of the MEMS is systematic. By an optimized design both effects can at least partially compensate each other yielding an improved temperature characteristic. Since LED, PD, and readout circuit can be operated at remote locations at fixed temperatures, if glass fibres are used, the device is nearly unaffected by temperature changes.

Given these beneficial properties and the possibility to mass-produce the sensor with the mature techniques of Si micromachining, this cheap, light-weight MEMS sensor will have an impact on technical, environmental, personal safeguarding, and meteorological applications. For instance, many open questions in lightning research depend on the knowledge of the local electric field before and during thunderstorms. Furthermore, the sensor can be applied in mobile and handheld devices for warning systems, e.g. lightning warning or near high-voltage power lines.

Methods

Analysis and enhancement of the electrostatic force

A simplified analytical model was established for the basic understanding of the electromechanical transduction (see Eq. 1). The electrostatic force was calculated for one half of an ideally conducting sphere placed in a homogeneous electric field pointing in z -direction. For arbitrary geometries such as the presented E-field sensor, the geometrical prefactor of the sphere has to be replaced by a tensor a_{ij} which relates each electric field

component to each force component. Thus, force components can arise that are normal to the direction of E_0 .

Since these calculations are hard to carry out analytically for the given device geometry, the electrostatic forces were studied with finite element method (FEM) simulations (COMSOL Multiphysics®). This helped to improve the electromechanical transduction by examining different geometries and, thus, the layout of the sensor. Since the sensor is intended for operation in the quasi-static regime ($f < f_0$), these calculations were conducted with the Electrostatics module. Each Si geometry studied here, was set to a floating potential boundary condition. This corresponds to the assumption of an ideal conductor, which is sufficiently accurate in this frequency regime. The Si geometries were placed inside a cuboid the size of the volume between the capacitor plates of the measurement setup. Two opposing faces of this cuboid were each set to a fixed Electric Potential boundary condition, such that the interior of the cuboid is filled with a uniform E-field in x -direction. Any electrostatic force was extracted by the Force Calculation interface.

First, it was investigated, whether force components normal to the direction of the E-field arise. Supplementary Figure 2 shows the corresponding force components for an electric field pointing in x -direction. While there are indeed other components, the wanted x -component is by far the largest.

Another point was to compare the more straightforward bare layout with the semi-covered one, which is less fragile and to investigate the influence of the gap width x_r on the electrostatic force F_{es} . This was done by employing a semi-covered Si geometry and calculating the electrostatic forces for a parametric sweep of $x_r \in [5 \mu\text{m}, 10 \text{ cm}]$. Thereby, the position of MEMS domain A did not change. For the largest value of this sweep, the MEMS domain B lied outside of the E-field domain, which corresponds to the bare case. The corresponding results for a field of $E_0 = 5.26 \text{ kV/m}$ are depicted in Supplementary Figure 3. This reveals that the semi-covered layout is the favourable one and that for values $x_r \lesssim 200 \mu\text{m}$, the force is roughly proportional to $1/x_r$. Furthermore, it was investigated, whether the orthogonal force components excite mechanical modes of the MEMS other than the fundamental mode. This was done with a frequency domain analysis within the Structural Mechanics module in which the moveable mass of the MEMS was excited with the full force vector F_{es} for an input field of again $E_0 = 5.26 \text{ kV/m}$. It can be seen in Supplementary Figure 4 that apart from a negligible effect at the second eigenmode, only the fundamental mode is excited.

In addition, the temperature dependency of the sensor was investigated by FEM simulations solving for the eigenfrequencies in a parametric sweep of the temperature $T \in [232 \text{ K}, 393 \text{ K}]$. The results depicted in Supplementary Figure 5 exhibits the temperature dependency of the fundamental mode f_0 and the associated stiffness k . They suggest a temperature dependency with a change of k in the range of roughly 10% in a temperature range from -40 to $+50^\circ\text{C}$. Since the temperature dependency of silicon itself is small [27], this variance can be attributed to thermally induced stresses and expansions. Hence, with an improved suspension this variance can be lowered even further. In addition, the systematic nature of the dependency allows an automatic compensation of the sensitivity of the sensor.

MEMS fabrication

The fabrication process of the sensors is based on silicon on insulator (SOI) technology on a wafer-level scale. The individual steps are summarised in Supplementary Figure 1. In the first step, the microstructures comprising the moveable part of the optical shutter were patterned by photolithography and deep reactive ion etching (DRIE, Bosch process) of the device layer (thickness 50 μm) of a 100 mm SOI wafer. Note that at this point the two domains A and B had to be connected by a small bridge at the edge of the chip, otherwise the wafer would fall apart. Afterwards, a protective layer of photoresist was applied to support and screen the structures during the following process steps. In order to ensure the movability of the motional mass, the regions of the handle layer (thickness 350 μm) lying beneath the microstructures were removed by a further DRIE step. The remaining intermediate SiO_2 layer was then removed by wet chemical etching with buffered hydrofluoric acid in order to release the movable microstructures. The subsequent dissolution of the protective photoresist and cleaning in oxygen plasma finalised the silicon parts. The stationary part of the optical shutter was patterned onto a glass wafer by photolithography and physical vapor deposition of Cr. After that, the glass wafer was bonded onto the top side (device side) of the SOI wafer with SU-8 as bonding agent and spacer. The SU-8 spacer was patterned by photolithography into frames surrounding the individual chips. This ensured a spacing of roughly 15 μm between glass and SOI wafer. In a final fabrication step the bonded wafer was diced into $6 \times 6 \text{ mm}^2$ chips with a wafer saw ensuring the electrical separation of the two Si domains A and B which at this point were held together only by the SU-8 and the glass chip. Ten copies of each layout were placed onto the wafer in order to account for possible losses especially during the dicing step and to investigate reproducibility.

Mechanical and E-field measurements

Each MEMS chip was characterised with a mechanical setup to test their functionality and determine their mechanical properties (fundamental frequency ω_0 , damping γ and quality factor Q) prior to E-field measurement. The chips were stacked together with a green LED (Osram LT-A673-N2S1-35) and a Si photodiode (Vishay TEMD5510FX01) and mounted onto a piezoelectric shaker [29] providing a constant amplitude vibration in a frequency range from 100 Hz to 3 kHz. The output current of the photodiode was converted into the output voltage with a transimpedance amplifier consisting of an operational amplifier OPA404 and a feedback resistor of 1 M Ω . The LED current was set to 20 mA and the PD bias to -4 V [30, 31, 32]. The shaker and the readout circuit were placed inside a metal housing to avoid stray light and electromagnetic coupling from the environment. The metal housing allowed for the laser of a Doppler-vibrometer (Polytec MSA-400) to reach the edge of the MEMS chip. Using the vibrometer it was possible to track the input vibration for reference. The analog output signals of both the laser-Doppler vibrometer and the readout circuit were recorded with lock-in amplifiers (Stanford SR830). The measurement procedure was completely automated and controlled by a PC.

The fundamental frequencies ω_0 agreed well within each group (see Table 1). Also the decay parameters γ were in agreement with analytical models [33], even though the variance, especially of group Ch00, is quite high. As expected, the yield of the fabrication is

rather low and only four chips (five in group Ch10) in each layout group were functional after the fabrication processes. These mechanical functional chips were characterised regarding their behaviour in an electrical field.

For these electric field measurements a different setup was built up. The chip was mounted onto a transparent adhesive tape on an acrylic structure such that it is located in the centre point between two quadratic capacitor plates of 2.7 cm edge length. These plates are 1.9 cm apart and provide a well-defined uniform E-field. These components were fixed to a U-shaped optical workbench holding a low-emission angle LED (Thorlabs LED528EHP, $\lambda_{\text{peak}} = 525 \text{ nm}$) and a large area Si photodiode (Centronic OSD15-5T); see Fig. 3. The workbench was grounded in order to minimise unwanted coupling of the electric field to the optoelectronic components and their respective connections to the readout circuit and mounted on a vibration-damped breadboard. The readout circuit was the same as for the mechanical characterisation. The capacitor plates were supplied with a sinusoidal AC voltage. In order to achieve high electric fields, a high-voltage wideband amplifier (Tabor Electronics 9200A) was used with which voltages up to 400 V (or fields up to $\sim 21 \text{ kV/m}$) can be reached. The LED current was again set to 20 mA and the PD bias to -4 V . The output voltage of the readout circuit was again recorded by a lock-in amplifier (Stanford SR830), only this time at the second harmonic of the input frequency f_{in} . Note that, due to the different lighting situation, however, the results from the mechanical measurements can not be taken as reference to estimate the actual displacement of the moving part in this setup. The relatively large variances are mainly due to the manual positioning of the MEMS in the setup which has a great impact on the light path through the chip. This issue is expected to be accounted for in future devices with optical fibre connections.

For very low frequencies $f \lesssim 0.5 \text{ Hz}$, the finite conductivity of the air which depends on the ambient conditions (mostly humidity) has to be taken into account. The two silicon domains effectively constituting a capacitance C and the parasitic resistance of the air R_p form a high pass. Measurements of the exponential decay behaviour have shown that the time constant $\tau = R_p C$ is roughly in the range of 800 ms (see Supplementary Figure 6). Therefore, the measurement setup was transferred into a vacuum chamber in order to increase R_p .

Supplementary Figure 7 shows the transient response of a MEMS sensor to a quasi-arbitrary field-variation recorded with an oscilloscope. The observed field resolution is much worse compared to the one of the lock-in method. However, the related measurement resolutions suffer from a wide signal bandwidth and the excessive noise level of the 200 MHz sampling oscilloscope used (Agilent DSO-X2024A). The moving average trace in Supplementary Figure 7 indicates the possible improvement by filtering techniques. This measurement was taken at a pressure of roughly 0.07 mbar. Therefore, in order to achieve reliable results for frequencies lower than 0.5 Hz, a vacuum package might be necessary.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- [1]. Hill, DA., Kanda, M. The measurement, instrumentation, and sensors handbook XXV, section 47, Electric Field Strength. CRC Press LLC and IEEE Press; 1999.
- [2]. Kirkham, H. On the measurement of stationary electric fields in air. Conference on Precision Electromagnetic Measurements; 2002. URL <http://trs-new.jpl.nasa.gov/dspace/handle/2014/11802>
- [3]. Vasa N, Kawata Y, Tanaka R, Yokoyama S. Development of an electric field sensor based on second harmonic generation with electro-optic materials. Journal of Materials Processing Technology. 2007; 185:173–177. URL <http://linkinghub.elsevier.com/retrieve/pii/S092401360600272X>.
- [4]. Meier T, Kostrzewa C, Petermann K, Schuppert B. Integrated optical e-field probes with segmented modulator electrodes. Journal of Lightwave Technology. 1994; 12:1497–1503.
- [5]. Williams K, De Bruyker D, Limb S, Amendt E, Overland D. Vacuum steered-electron electric-field sensor. Journal of Microelectromechanical Systems. 2014; 23:157–167.
- [6]. Ando B, Baglio S, Marletta V, Bulsara AR. A nonlinear electric field sensor that exploits coupled oscillator dynamics: The charge collection mechanism. IEEE Transactions on Instrumentation and Measurement. 2013; 62:1326–1333. URL <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6417025>.
- [7]. Berthelier J, et al. ICE, the electric field experiment on DEMETER. Planetary and Space Science. 2006; 54:456–471. URL <http://linkinghub.elsevier.com/retrieve/pii/S0032063305002072>.
- [8]. Peng C, Yang P, Zhang H, Guo X, Xia S. Design of a novel closed-loop SOI MEMS resonant electrostatic field sensor. Procedia Engineering. 2010; 5:1482–1485. URL <http://linkinghub.elsevier.com/retrieve/pii/S1877705810009446>.
- [9]. Pierce ET. Atmospheric Electricity-Some Themes. Bulletin of the American Meteorological Society. 1974; 55:1186–1194. URL [http://journals.ametsoc.org/doi/abs/10.1175/1520-0477\(1974\)055%3C1186:AEST%3E2.0.CO%3B2](http://journals.ametsoc.org/doi/abs/10.1175/1520-0477(1974)055%3C1186:AEST%3E2.0.CO%3B2).
- [10]. Williams E, Mareev E. Recent progress on the global electrical circuit. Atmospheric Research. 2014; 135–136:208–227. URL <http://linkinghub.elsevier.com/retrieve/pii/S0169809513001543>.
- [11]. Zhang, Bo, Wang, Wenzhuo, He, Jinliang. Impact factors in calibration and application of field mill for measurement of DC electric field with space charges. CSEE Journal of Power and Energy Systems. 2015; 1:31–36. URL <http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=7281125>.
- [12]. Horenstein MN, Stone PR. A micro-aperture electrostatic field mill based on MEMS technology. Journal of Electrostatics. 2001; 51–52:515–521. URL <http://www.sciencedirect.com/science/article/pii/S0304388601000481>.
- [13]. Peng, C., Chen, X., Bai, Q., Luo, L., Xia, S. A novel high performance micromechanical resonant electrostatic field sensor used in atmospheric electric field detection. Micro Electro Mechanical Systems, 2006. MEMS 2006 Istanbul. 19th IEEE International Conference on; IEEE; 2006. p. 698-701. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1627895
- [14]. Kalinowski, D., Redlich, S., Jager, D. Novel micromachined fiber-optic e-field sensor. LEOS'99. IEEE Lasers and Electro-Optics Society 1999 12th Annual Meeting; IEEE; 1999. p. 385-386. URL http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=813645
- [15]. Rogers AJ. Optical measurement of current and voltage on power systems. IEE Journal on Electric Power Applications. 1979; 2:120–124. URL <http://digital-library.theiet.org/content/journals/10.1049/ij-epa.1979.0019>.
- [16]. Soref RA, Bennett B. Electrooptical effects in silicon. IEEE Journal of Quantum Electronics. 1987; 23:123–129.

- [17]. Toney, JE., et al. Advanced materials and device technology for photonic electric field sensors. Proc SPIE 8519, Nanophotonics and Macrophotonics for Space Environments VI. Taylor, EW., et al., editors. 2012. 851904
- [18]. Berger J, Petermann K, Föhling H, Wust P. Calibrated electro-optic e-field sensors for hyperthermia applications. Physics in medicine and biology. 2001; 46:399. URL <http://iopscience.iop.org/0031-9155/46/2/309>. [PubMed: 11229722]
- [19]. Barthod, C., Passard, M., Fortin, M., Galez, C., Bouillot, J. Design and optimization of an optical high electric field sensor; 2000 Conference on Precision Electromagnetic Measurements Digest; 2000. p. 423-424.
- [20]. Chmielak B, et al. Pockels effect based fully integrated, strained silicon electro-optic modulator. Optics express. 2011; 19:17212–17219. URL <http://www.opticsinfobase.org/abstract.cfm?uri=oe-19-18-17212>. [PubMed: 21935084]
- [21]. Zeng R, Wang B, Niu B, Yu Z. Development and application of integrated optical sensors for intense e-field measurement. Sensors. 2012; 12:11406–11434. URL <http://www.mdpi.com/1424-8220/12/8/11406/>. [PubMed: 23112663]
- [22]. Bohnert, K., Gabus, P., Brändle, H., Khan, A. Fiber-optic current and voltage sensors for high-voltage substations; Proceedings of the 16th International Conference on Optical Fiber Sensors; Nara, Japan. 13–17; 2003.
- [23]. Landau, L., Lifshitz, E., Pitaevski, L. Electrodynamics of Continuous Media, vol. 8 of Course of Theoretical Physics. Vol. 8. Butterworth-Heinemann; 1984.
- [24]. Hortschitz W, et al. An Optical In-Plane MEMS Vibration Sensor. Sensors Journal, IEEE. 2011; 11:2805–2812.
- [25]. Hortschitz W, et al. MOEMS Vibration Sensor for Advanced Low-frequency Applications with pm Resolution. Procedia Engineering. 2014; 87:835–838.
- [26]. Middlemiss R, et al. Measurement of the earth tides with a mems gravimeter. Nature. 2016; 531:614–617. [PubMed: 27029276]
- [27]. Zhang W-M, Yan H, Peng Z-K, Meng G. Electrostatic pull-in instability in MEMS/NEMS: A review. Sensors and Actuators A: Physical. 2014; 214:187–218.
- [28]. Boyd EJ, Li L, Blue R, Uttamchandani D. Measurement of the temperature coefficient of Young's modulus of single crystal silicon and 3c silicon carbide below 273 K using micro-cantilevers. Sensors and Actuators A: Physical. 2013; 198:75–80.
- [29]. Encke J, et al. Proc SPIE 8763, Smart Sensors, Actuators, and MEMS VI. 2013; 8763:876315–876315. DOI: 10.1117/12.2017405
- [30]. Hortschitz W, et al. Robust Precision Position Detection With an Optical MEMS Hybrid Device. IEEE Transactions on Industrial Electronics. 2012; 59:4855–4862.
- [31]. Hortschitz, W., et al. Optimized Hybrid MOEMS Sensors Based on Noise Considerations; Proceedings of the IEEE Sensors; Taipei, Taiwan. 2012. p. 4
- [32]. Hortschitz, W., et al. Receiver and amplifier optimization for hybrid MOEMS; Proceedings of the IEEE Sensors; Taipei, Taiwan. 2012. p. 4
- [33]. Kainz A, et al. Accurate analytical model for air damping in lateral mems/moems oscillators. Sensors and Actuators A: Physical. 2017; 255:154–159. URL <http://www.sciencedirect.com/science/article/pii/S0924424716312158>.

Figure 1. Illustration of the charge separation and occurring electrostatic forces on a conducting sphere in an external electric field.

a) Forces and field lines of a conducting sphere with radius R in an $\mathbf{E}$ -field $\mathbf{E}$. The electric field polarises the sphere. b) A conductive spring connecting the oppositely charged regions of the sphere elongates due to the electrostatic force F_{es} while maintaining the polarisation.

Figure 2. MEMS embodiment for electric field transducer.

a) Schematic cross-section of the electric field transducer. The light flux emitted by an LED is modulated by two microstructured optical shutters. The output signal of the photodiode depends on the deflection δx of the movable aperture which is induced by an external electric field E_0 . b) Possible layouts for the electric field sensor. The left schematic (bare structure) corresponds to the straightforward implementation of the charge separation corresponding to Fig. 1b. The right one (semi-covered structure) increases the force by a stationary Si part that works as a field concentrator. c) Graphic depiction of a MEMS chip indicating the SU-8 bonding procedure. d) SEM image of a chip taken during fabrication.

Figure 4. Response of a MEMS sensor (group Ch00) to the input electric fields.

a) The quadratic transduction of the E-field effects that the resonance frequency is observed at $f_{\text{in}} = f_0/2$, here at 139.2 Hz instead of 292.6 Hz. The cutoff at the resonance of the top curve is due to the saturated voltage range of the lock-in. b) Strength of the response $S_{\text{es}} E_0^2$ as function of the electric field amplitude E_0 . The circles correspond to the curves on the left and the red dashed line to the function $f(E_0) = S_{\text{es}} E_0^2$ with the mean value of $S_{\text{es}} = 3.6 \cdot 10^{-4} \text{ Vs}^{-2}/(\text{V/m})^2$ obtained from the least-squares fits of the corresponding data. The coefficient of determination for the linear fit function $f(E_0^2)$ was determined to be $R^2 = 0.9985$.

Table 1
Results of the mechanical characterisation and E-field measurements for different chip designs.

	k (N/m)	x_r (μm)	ω_0 (1/s)	Q (1)	S_{es} ($\mu\text{Vs}^{-2}/(\text{V/m})^2$)	r_{es} ($(\text{V/m})/\sqrt{\text{Hz}}$)	$\#^a$
Ch00	1	10	1823 ± 33	10.85	234 ± 101	221 ± 69	4/10
Ch01	1	20	1891 ± 62	30.31	131 ± 38	294 ± 89	4/10
Ch10	2	10	2663 ± 103	17.89	268 ± 82	272 ± 68	5/10
Ch11	2	20	2572 ± 193	42.51	146 ± 32	399 ± 60	4/10

^aThe symbol (#) donates the number of chips in the individual groups. The given uncertainty ranges specify the root mean square errors of respective parameter values.