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

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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 bulky, suffer from a strong temperature dependency or severely distort the electric field, and thus require 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 V m^{-1} Hz^{-1/2} with a measurement range of up to tens of kilovolts per metre in the quasi-static regime (<300 Hz). We also show that it should be possible to achieve resolutions of around 1 V m^{-1} Hz^{-1/2} by fine-tuning the sensor embodiment. These MEMS devices are compact and could be mass produced easily for wide application.

It is difficult to measure electric field strength without interference by the measuring instrument. Dielectric bodies develop surface charges that 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 have to be grounded or connected to large conductors to establish a reference potential. Current measurement systems for static and low-frequency electric fields can be divided into two general categories: direct electrical conversion, comprising double probes of electrical potential as well as field mills3−5 and electrooptical systems6−8. A variety of alternative approaches also exist9−11, but they all suffer from drawbacks such as limited lifetime or scalability. Double probes can achieve resolutions of ~0.1 V m^{-1} Hz^{-1/2} (ref. 3), but reaching these values relies on a diluted plasma environment, precisely shaped probe electrodes exhibiting low-workfunction surfaces and probe interdistances of several metres. As the potential probes are usually active devices, carefully designed and 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, which has a typical resolution of ~50 V m^{-1} Hz^{-1/2} (ref. 9); for comparison, the fair-weather electric field at ground level is ~100 V m^{-1} and fields inside thunderclouds can be as high as 50 kV m^{-1} (refs 10,11). However, field mill measurements are inherently error-prone and strongly depend on the immediate environment. Conventional field mills are also relatively bulky3−5, and electrooptical systems6−8 suffer from a strong temperature dependency due to the pyroelectric effect and thermal expansion of the material11, and no optical sensor has so far satisfactorily solved this problem3−5.

### 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 electric field \( \mathbf{E} \), the free charge carriers inside the conductor redistribute, in contrast to the lattice-bound opposite charges. This polarization 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 their only connection in the form of a conducting spring, one can observe an elongation of the spring due to the electric field (Fig. 1a,b). This is due to the electrostatic force pulling on the individual charged surfaces and the conductivity of the spring by which the polarization 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 the \( z \) direction (where \( \mathbf{e}_z \) is the unit vector in the \( z \) direction), the total electrostatic force experienced by, for example, the right half of the full sphere, that is, the positively charged region, can be calculated analytically23 and equals

\[
F_x = F_y = F_z = \frac{9}{4} R^2 \varepsilon_0 E_0^2 = a_x E_0^2, \tag{1}
\]
The displacement of the spring-suspended Si part is read out optically by detecting the light flux modulated by the device\(^2,23\). This is achieved by an optical shutter composed of a stationary (patterned by Cr deposited on glass) and a movable aperture array (etched into Si, displaced by \(F_{es}\)) of rectangular holes placed on top of each other (Fig. 2a). Each of the grids bears a large number of \(N_h = 147 \times 22 = 3,234\) 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 movable part is displaced, the transmitted light flux changes according to the following equation.

\[
f = m(\omega_0^2 - \omega^2 + 2i\gamma \omega) = \omega_0 E_0^2 / (\omega_0^2 - \omega^2 + 2i\gamma \omega)
\]

The corresponding area change is given by \(\delta A_{\text{sh}} = N_h l_h \delta x\). Thus, the overall intrinsic displacement sensitivity \(S_{\text{int}} \propto N_h l_h\) is determined by the number of holes. The transfer characteristic of the transducer is therefore given as

\[
A(\omega) = \frac{S_{\text{trans}}}{m(\omega_0^2 - \omega^2 + 2i\gamma \omega)} = \frac{S_{\text{trans}}}{m(\omega_0^2 - \omega^2 + 2i\gamma \omega)}
\]

where \(S_{\text{trans}}\) is the electromechanical sensitivity and \(\omega_0\) is the resonance angular frequency of the mechanical system. The transfer function \(T(\omega)\) is defined as

\[
T(\omega) = \frac{m(\omega_0^2 - \omega^2 + 2i\gamma \omega)}{m(\omega_0^2 - \omega^2 + 2i\gamma \omega)}
\]

with the angular frequency \(\omega\) and the damping factor \(\gamma\) of the system. The resonance frequency \(\omega_0 = \sqrt{k/m}\) is determined by the number of holes.

\[\omega_0 = \sqrt{k/m}\]

where \(k = 4\pi R^2/4\) takes into account the highly symmetric geometry of the sphere and \(\varepsilon_0\) is the vacuum permittivity. The left half of the sphere experiences an equally strong force that points in the opposite direction. Thus, the total force on the sphere equals zero. For less symmetric shapes, the geometric prefactor \(a\) has to be replaced by a tensor with components \(a_{ij}\) and equation (1) would then read in index notation

\[
F_{es,i} = a_{ij} \varepsilon_0 E_0^2 E_{0,j}
\]

in the spectral domain. From this fundamental equation, we have shown that the mechanical system can be described by a harmonic oscillator with low-pass characteristic and transfer function

\[
H(\omega) = \frac{1}{m(\omega_0^2 - \omega^2 + 2i\gamma \omega)}
\]

where \(i = \sqrt{-1}\), the tilde symbol indicates frequency domain representation, and \(\omega\) denotes the angular frequency of the force excitation. The resonance frequency \(\omega_0 = \sqrt{k/m}\) and the decay parameter \(\gamma = d/(2m)\) in equation (2) define the spectral properties of the transducer entirely. The system response of the force–deflection conversion is governed by \(\tilde{X} = \tilde{H} F_{es}\). However, the quadratic dependence of \(F_{es}\) on \(E\) in equation (1) imposes a nonlinear conversion between force and electric field that involves a convolution \(X = \tilde{X} \ast (E^2 \tilde{E})\) in the spectral domain. From this fundamental relationship we can conclude that a unique back-calculcation from the measured deflection to the unknown electric field \(E(\omega)\) is only possible if its upper cutoff frequency is smaller than half of the cutoff frequency of the mechanical system \(\tilde{H}(\omega)\). In the remainder of this Article, the special case of a time-harmonic electric field will be studied intensively. For this time-harmonic electric field \(E(t) = E_0 \cos(\omega t)\), the general theory simplifies to an actuating force \(F_{es} \propto E_0^2 \cos^2(\omega t) = E_0^2 (1 + \cos(2\omega t))/2\) consisting of an a.c. component with twice the frequency of the electric field (that is, \(a f\) to \(2\omega\) conversion from electric field to force) and a d.c. component.

**MEMS implementation**

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 semicovered structure with a second Si domain separated from the moving part by a relatively narrow gap. The former poses the more direct implementation of the principle depicted in Fig. 1b, and the latter is the more effective one. The additional Si part (domain B) itself is subject to electrostatic actuation and thus concentrates the electric field inside the gap. This increases the force experienced by the moving Si part. We found that for gap widths \(x_{g} \lesssim 200 \, \mu\text{m}\), \(F_{es}\) is proportional to \(x_{g}^{-1}\) (see Methods). We therefore opted for the semicovered structure and the MEMS design as depicted in Fig. 2c,d. The flexible suspensions for the moving shutter were designed as U shapes instead of as straight beams to avoid the mechanical nonlinearities that usually occur at larger deflections. The Si parts of the MEMS were fabricated with silicon on insulator (SOI) technology on a wafer level scale. The stationary shutter was patterned onto a glass wafer, which was then bonded to the SOI wafer using a photosist (SU-8) as bonding promoter (Fig. 2c). After bonding, the two Si domains were held together by a glass chip and the connection in between was cut away during dicing of the wafer into individual chips (for more details see Methods). This separation is necessary, as any remaining connection would shield the moving mass from the field and render the device useless. Four variations of the layout, termed ChXX, were designed, which differ in spring stiffness and gap width. The first X in the name corresponds to the stiffness of the structure, which was set to \(k = 1 \, \text{N m}^{-1}\) and \(k = 2 \, \text{N m}^{-1}\), denoted by \(X = 0\) and \(X = 1\), respectively. Thus, the resonance frequencies of the layout and ChX1 should differ by a factor of \(\sqrt{2}\). The second X (\(X = 0,1\)) denotes the width of the separation gap of \(x_{g} = 10 \, \mu\text{m}\) and \(x_{g} = 20 \, \mu\text{m}\), respectively. The corresponding sensitivities should therefore differ by a factor of 2 (Table 1). Ten copies of each layout were fabricated.

**Characteristics of the MEMS device**

The MEMS sensors were characterized in two ways. First, the mechanical properties, that is, \(\omega_0\) and \(\gamma\) 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
characterization allowed us to test the functionality and determine 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 a.c. electric field with amplitudes ranging from 342 V m⁻¹ to 21 kV m⁻¹ 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 (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 nature of the transduction, this is equivalent to an electric field of ~153 V m⁻¹. With respect to the equivalent noise bandwidth ENBW of 0.78 Hz of the lock-in amplifier at an off-resonance measurement frequency of 100 Hz, this yields a resolution of $r_{\text{en}}=173 \text{ V m}^{-1} \text{ Hz}^{-1/2}$.

The measurement equipment limits the electric fields to $\leq 21.1 \text{ kV m}^{-1}$. We therefore estimate the dynamic range of this device by determining the maximum measurable electric field that 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 movable mass takes place. The electric field resulting in a deflection of $x_r/3 = 3.3 \mu m$ 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⁻¹.

The results for the electromechanics sensitivity $S_{\text{es}}$ for all layout groups are listed in Table 1. The values of $S_{\text{es}}$ incorporate only the electrostatic force and the intrinsic sensitivity of the device and are, therefore, independent of $\omega_0$ and $\gamma$. Thus, groups Ch01 and Ch11, which differ only by their stiffness or $\omega_0$, are equivalent with respect to $S_{\text{es}}$. They have the same gap $x_r=20 \mu m$ determining $F_e$ and the same optomechanical sensitivity $S$. Combining these groups, one finds $S_{\text{es,Ch01}}=(1.39 \pm 0.36) \times 10^{-4} \text{ V s}^{-2} \text{ (V m}^{-1})^-2$. The same is true for Ch10 and Ch00 with the same sensitivity $S$ but different $x_r = 10 \mu m$, yielding $S_{\text{es,Ch00}}=(2.68 \pm 0.94) \times 10^{-4} \text{ V s}^{-2} \text{ (V m}^{-1})^-2$. In the case of...
group Ch11, that is, the stiffer and less sensitive group, the maximum measurable electric field can be as high as 230 kV m⁻¹.

Conclusions
At the moment, the achieved field resolution is determined by the electronic noise of the readout circuit. The fundamental limit of the sensor, that is, Brownian noise, can be estimated by the mean noise force \( F_{th} = \sqrt{4 k_B T m d} \), where \( k_B \), \( T \) and \( d = my \) are the Boltzmann constant, the temperature and the damping coefficient, respectively. Therefore, the equivalent displacement is \( \delta x_{th} = \sqrt{4 k_B T m Q} = 0.56 \text{pm} \text{Hz}^{-1/2} \) with a motional mass of \( m = 6.43 \times 10^{-10} \text{kg} \). The displacement sensitivity for the presented electric field measurement configuration was estimated by tapping on the side of the set-up to achieve a displacement larger than the width of one hole, that is, >10 μm. 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 μm. The fundamental electric field resolution for the depicted designs would therefore be \( r_{th} = 40.6 \text{V m}^{-1} \text{Hz}^{-1/2} \). Following the results obtained by the FEM simulations, future devices with a resolution below 1 V m⁻¹ Hz⁻¹/2 are feasible by reducing the gap width \( x \), and increasing the number of holes \( N \), and, thus, the sensitivity \( S_w \). 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 the Si of the MEMS part (in the range of 50 ppm K⁻¹; ref. 29) combined with thermal expansions in the range of 2.3 ppm K⁻¹ mainly affecting spring stiffness. Hence, the temperature dependence of the MEMS is systematic. With an optimized design, both effects can at least partially compensate each other, yielding an improved temperature characteristic. The light-emitting diode (LED), photodiode (PD) and readout circuit can be operated at remote locations at fixed temperatures, so 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 available for Si micromachining, this cheap, lightweight MEMS sensor will have an impact on technical, environmental, personal safeguarding and meteorological applications. For instance, many open questions in lightning research depend on knowledge of the local electric field before and during thunderstorms. Furthermore, the sensor can be applied in mobile and handheld devices for warning systems, for example, for lightning warning or near high-voltage power lines.

Methods
Analysis and enhancement of electrostatic force. A simplified analytical model was established to achieve a basic understanding of electromechanical transduction (equation (1)). The electrostatic force was calculated for one half of an ideally conducting sphere placed in a homogeneous electric field pointing in the \( z \) direction. For arbitrary geometries such as the presented \( E \)-field sensor, the geometrical prefactor of the sphere has to be replaced by a tensor \( a_{ij} \) that relates each electric field component to each force component. Thus, force components can arise that are normal to the direction of \( E_0 \).

Because 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. The sensor is intended for operation in the quasi-static regime \(( f < f_0 )\), so 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 equivalent to the size of the volume between the capacitor plates of the measurement set-up. Two opposing faces of this cuboid were each set to a fixed electric potential boundary condition, so that the interior of the cuboid was filled with a uniform \( E \)-field in the \( x \) direction. Any electrostatic force was extracted by the ‘Force Calculation’ interface.

It was first investigated whether force components arise normal to the direction of the \( E \)-field. Supplementary Fig. 2 shows the corresponding force components for an electric field pointing in the \( x \) direction. Although there are other components, the wanted \( x \) component is by far the largest. We also compared the more straightforward bare layout with the semicovered one, which is less fragile, and investigated the influence of the gap width \( x \) on electrostatic force \( F_x \). This was done by employing a semicovered Si geometry and calculating the electrostatic forces for a parametric...
in which the movable mass of the MEMS was excited with the full force vector $F_0$ for an input field of $E_0 = 5.26 \text{ kV m}^{-1}$. It can be seen in Supplementary Fig. 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 $T$. The results depicted in Supplementary Fig. 5 show 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 $+50 \degree C$. Because the temperature dependency of $Si$ itself is small, this variance can be attributed to the individual 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 for the sensors is based on SOI technology on a wafer-level scale. The initial steps are summarized in Supplementary Fig. 1. In the first step, the microstructures comprising the movable part of the optical shutter were patterned by photolithography and deep reactive ion etching (DRIE, Bosch process) of the device layer (thickness 50 $\mu$m) of a 100 nm 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 the protective layer of photoresist was applied to protect and screen the structures during the subsequent process steps. To ensure the movability of the motional mass, the handle layer regions (thickness 350 $\mu$m) 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 to release the movable microstructures. Subsequent dissolution of the protective photoresist and cleaning in isopropyl alcohol finally released the parts. The stationary part of the optical shutter was patterned onto a glass wafer by photolithography and physical vapour deposition of Cr. The glass wafer was then 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 $15 \mu$m between the glass and SOI wafer. In a final fabrication step the bonded wafer was diced into 6 x 6 mm chips with a 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 to account for possible losses, especially during the dicing step, and to investigate reproducibility.

**Mechanical and E-field measurements.** Each MEMS chip was characterized with a mechanical set-up to test its functionality and determine its mechanical properties (fundamental frequency $\omega_0$, damping $\gamma$ and quality factor $Q$) before E-field measurement. The chips were stacked together with a green LED (Osram LT-A673-N251-35) and a Si photodiode (Vishay TEMD5510FX01) and mounted onto a piezoelectric shaker 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$\Omega$. The LED current was set to 20 mA and the PD bias to $-4$ V (refs 42, 43). 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 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 $\omega_0$ agreed well within each group (Table 1). The decay parameters $\gamma$ were also in agreement with analytical models, even though the variance, especially of group Ch00, was quite high. As expected, the yield of the chip was rather low and only four chips (five in group Ch10) in each layout group were functional. The fabrication of the functional chips were characterized regarding their behaviour in an electric field.

For these electric field measurements a different set-up was built. The chip was mounted onto a transparent adhesive tape on an acrylic structure so that it was located in the centre point between two quadratic capacitor plates (2.7 cm edge lengths). These plates were 1.9 cm apart and provide a well-defined uniform E-field. The E-field components were fixed to a U-shaped vacuum chamber to increase the electric field detection. These 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 characterization. The capacitor plates were supplied with a sinusoidal a.c. voltage. 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 $\pm 21 \text{kV m}^{-1}$) 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 $f_0$. Note that, due to the different lightening situation, however, the results from the mechanical measurements cannot be taken as a reference to estimate the actual displacement of the moving part in this set-up. The relatively large variances are mainly due to the manual positioning of the MEMS in the set-up, 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 $f < 0.5 \text{ Hz}$, the finite conductivity of the air, which depends on the ambient conditions (mostly humidity), has to be taken into account. The two Si domains, effectively constituting a capacitance $C$ and parasitic resistance of the air $R_p$ form a high-pass filter. Measurements of the exponential decay behaviour have shown that the time constant $\tau = R_p C = \approx 800 \text{ ms}$ (Supplementary Fig. 6). Therefore, the measurement set-up was transferred into a vacuum chamber to increase $R_p$.

Supplementary Fig. 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 than that 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 Fig. 7 indicates a possible improvement by using filtering techniques. This measurement was taken at a pressure of $\approx 0.07 \text{ mbar}$ so, to achieve reliable results for frequencies lower than 0.5 Hz, a vacuum package might be necessary.

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

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**References**

1. Hill, D. A. & Kanda, M. The Measurement, Instrumentation, and Sensors Handbook XXV, Section 47, Electric Field Strength (ed. Webster, J. G.) (CRC Press, Boca Raton, FL, 1999).
2. Kirkham, H. On the measurement of stationary electric fields in air. Conf. Precision Electromagnetic Measurements (2002), https://trs-new.jpl.nasa.gov/handle/21.11001/11902.
3. Vasa, N., Kawata, Y., Tanaka, R. & Yokoyama, S. Development of an electric field sensor based on second harmonic generation with electro-optic materials. J. Mater. Process. Technol. 185, 173–177 (2007).
4. Meier, T., Kostrzewa, C., Petermann, K. & Schuppert, B. Integrated optical E-field probes with segmented modulator electrodes. J. Lightwave Technol. 12, 1497–1503 (1994).
5. Williams, K., De Bruyker, D., Limb, S., Amendt, E. & Overland, D. Vacuum steered-electron electric-field sensor. J. Microelectromech. Syst. 23, 157–167 (2014).
6. Aindo, B., Baglin, S., Marletta, V. & Bulsara, A. R. A nonlinear electric field sensor that exploits coupled oscillator dynamics: the charge collection mechanism. IEEE Trans. Instrum. Meas. 62, 1326–1333 (2013).
7. Berthelier, J. J. et al. ICE, the electric field experiment on DEMETER. Planet. Space Sci. 54, 456–471 (2006).
8. Peng, C., Yang, P., Zhang, H., Guo, X. & Xia, S. Design of a novel closed-loop SOI MEMS resonant electrostatic field sensor. Proc. Eng. 5, 1482–1485 (2010).
9. Williams, K., de Bruyker, D., Limb, S., Amendt, E. & Overland, D. Vacuum steered-electron electric-field sensor based on second harmonic generation with electro-optic materials. J. Mater. Process. Technol. 185, 133–136 (2007).
10. Berthelier, J. J. et al. ICE, the electric field experiment on DEMETER. Bull. Am. Meteorol. Soc. 92, 2088–2095 (2011).
11. Zhang, B., Wang, W. & He, J. Impact factors in calibration and application of field mill for measurement of DC electric field with space charges. CSEE J. Power Energy Syst. 2, 135–136 (2016).
12. Berthelier, J. J. et al. ICE, the electric field experiment on DEMETER. Planet. Space Sci. 54, 456–471 (2006).
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. 19th IEEE Int. Conf. Micro Electro Mechanical Systems 2006, 698–701 (IEEE, 2006).
14. Kalinowski, D., Redlich, S. & Jager, D. Novel micromachined fiber-optic E-field sensor. IEEE Lasers and Electro-Optics Society 1999 12th Annual Meeting Vol. 1, 385–386 (IEEE, 1999).

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15. Rogers, A. J. Optical measurement of current and voltage on power systems. *IEE J. Electric Power Appl.* 2, 120–124 (1979).

16. Soref, R. A. & Bennett, B. Electrooptical effects in silicon. *IEEE J. Quantum Electron.* 23, 123–129 (1987).

17. Toney, J. E. et al. in *Proc. SPIE 8519, Nanophotonics and Macrophotonics for Space Environments VI* (eds Taylor, E. W. et al.) 851904 (SPIE, Bellingham, Washington, 2012).

18. Berger, J., Petermann, K., Fühling, H. & Wust, P. Calibrated electro-optic E-field sensors for hyperthermia applications. *Phys. Med. Biol.* 46, 399 (2001).

19. Barthod, C., Passard, M., Fortin, M., Galez, C. & Bouillot, J. Design and optimization of an optical high electric field sensor. *2000 Conf. Precision Electromagnetic Measurements Digest* 423–424 (2000).

20. Bohnert, K., Gabus, P., Brändle, H. & Khan, A. Fiber-optic current and voltage sensors for high-voltage substations. *Proc. 16th Int. Conf. Optical FiberSensors* 13–17 (Nara, Japan, 2003).

21. Chmielak, B. et al. Pockels effect based fully integrated, strained silicon electro-optic modulator. *Opt. Express* 19, 17212–17219 (2011).

22. Landau, L., Lifshitz, E. & Piaevski, L. *Electrodynamics of Continuous Media* (Butterworth-Heinemann, Oxford, UK, 1984).

23. Middlemiss, R. et al. Measurement of the Earth tides with a MEMS gravimeter. *Nature* 531, 614–617 (2016).

24. Zhang, W.-M., Yan, H., Peng, Z.-K. & Meng, G. Electrostatic pull-in instability in MEMS/NEMS: a review. *Sens. Actuat. A* 214, 187–218 (2014).

25. Encke, J. et al. A miniaturized linear shaker system for MEMS sensor characterization. *Proc. SPIE 8763, SmartSensors, Actuators, and MEMS VI* 876315–876315 (2013); http://dx.doi.org/10.1117/12.2017405

26. Zeng, R., Wang, B., Niu, B. & Yu, Z. Development and application of integrated optical sensors for intense E-field measurement. *Sensors* 12, 11406–11434 (2012).

27. Hortschitz, W. et al. Robust precision position detection with an optical MEMS hybrid device. *IEEE Trans. Indust. Electron.* 59, 4855–4862 (2012).

28. Hortschitz, W. et al. Optimized hybrid MOEMS sensors based on noise considerations. *Proc. IEEE Sensors* https://doi.org/10.1109/ICSENS.2012.6411322 (2012).

29. Kainz, A. et al. Accurate analytical model for air damping in lateral MEMS/ MOEMS oscillators. *Sens. Actuat. A* 255, 154–159 (2017).

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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 manufacturing the device, while F.Ko., M.S. and F.Ke. supported the measurements and the design of the devices. R.B. supported modelling and was involved in acquiring funding for the work. All authors contributed to the manuscript.

Competing interests

The authors declare no competing financial interests.

Additional information

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