Sensors and Actuators A 245 (2016) 76–84

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Micromachined ac/dc electric field sensor with modulated sensitivity

T. Chen, C. Shafai*, A. Rajapakse, J.S.H. Liyanage, T.D. Neusitzer

Department of Electrical and Computer Engineering, University of Manitoba, 75 Chancellor's Circle, Winnipeg, MB, R3T 5V6, Canada

ARTICLE INFO

Article history:
Received 26 August 2015
Received in revised form 18 April 2016
Accepted 24 April 2016
Available online 26 April 2016

Keywords:
Electric field
Electric field measurement
Electric field mill
MEFM
MEMS
Micromachining

ABSTRACT

This paper presents a compact ac/dc electric field sensor with adjustable sensitivity and measurement range. The sensor is fabricated using an SOI micromachining process, and consists of a metallized membrane supported by micro-springs. The sensor operates by monitoring membrane displacement due to incident electric fields. Unlike field mills, this sensor does not have rotating parts, avoiding associated wear and maintenance issues. High sensitivity is achieved by using a laser position monitoring system. Modulation of the incident electric field with a bias voltage on the sensing membrane is used to give the sensor a wide measurement range, from sub-1 V/m to MV/m. Bench top experimental measurements with both dc and ac fields demonstrated a resolution of 0.1 V/m and sensitivity of 180 mV/(V/m), with the sensor operating at resonance. Measurements under 20 kV simulated power line 75 cm from the sensor demonstrated a resolution of 17 V/m and sensitivity of 360 mV/(kV/m).

1. Introduction

Much of the modern electrical distribution grid is based on ac networks, however, recently there is increased interest in dc networks and hybrid ac/dc networks. This is due to several factors. For example, dc networks are of benefit for grid interconnectivity, and HVDC for transmission of power over very long distances, which can be the situation when connecting remote energy sources (hydroelectric, wind, solar) to urban areas [1]. HVDC technique also has benefit for undersea transmission due to low capacitance, resulting in lower cost [2]. Recent driving forces behind hybrid ac/dc networks are the increasing use of dc sources such as photovoltaic generation and battery storage, and dc loads for which power is lost in converting between ac and dc voltages. Load examples include solid state lighting, modern consumer electronics, and battery storage in electric vehicles.

There is need, therefore, for instrumentation for measuring dc electric fields. Beyond usage in the above examples, measurement of dc electric fields is also of benefit for environmental monitoring near HVDC power lines [3], for development of improved insulators, measure surface charge on equipment and tools, to ensure safety in live line work, and to measure voltage remotely in HVDC protection and control systems [4–6].

In recent decades, a variety of dc electric field sensors have been developed, most of them are based on three mechanisms: induction probes, optical sensors, and field mills. However, induction probes fail to provide long term measurement due to zero drift caused by charging. For example, the SVM2 hand held induction probe manufactured by AlphaLab requires manual re-zeroing every 20 min [7]. Optical sensors usually suffer from phase bias, temperature stability problems [8] and charging issues.

Field mills consist of an earthed perforated shutter and a set of electrodes underneath. When shutter periodically cover and expose the electrodes to the electric field, an induced ac current is generated. The strength of the current is proportional to the intensity of the electric field. Due to its long term stability, field mills have been widely used in atmospheric science to detect lightning and thunderstorms, and by power utilities. A typical commercial field mill consists of a rotating shutter, which consumes significant power relative to battery capacity. The maintenance of traditional rotating shutter field mills is high, and so operation costs, especially when installed along transmission lines far away from cities or in difficult terrain.

For the case when there is need to detect surface charge on small sized live line tools, the probe size needs to be to be smaller than the object size. Currently, in power engineering area, the smallest electric field meter has a probe size of 1 cm radius, which was demonstrated by Johnston and Kirkham in [9,10]. Therefore, in such applications, there is a need for an electric field sensor possessing characteristic of low power consumption, small size, high reliability, and also providing comparable sensitivity and signal quality with commercialize products.

---

* Corresponding author.
E-mail addresses: taoc@myumanitoba.ca (T. Chen), Cyrus.Shafai@umanitoba.ca (C. Shafai), Athula.Rajapakse@umanitoba.ca (A. Rajapakse), hiniduma@myumanitoba.ca (J.S.H. Liyanage), umneusit@myumanitoba.ca (T.D. Neusitzer).

http://dx.doi.org/10.1016/j.sna.2016.04.054
0924-4247/

Microfabrication techniques are able to produce tiny mechanical elements to form microelectromechanical system (MEMS). Micromachined electric field mills (MEFM) have been investigated for use in place of larger traditional rotating field mills. In 2001, Horenstein and Stone reported the first MEFM, which employed a comb drive to move a 10 μm × 10 μm aperture to cover and expose the underlying charge sense electrode [11]. Many types of MEFM have been reported by other groups [12–20]. Most MEFM designs have the shutter moving above the sensing electrodes and shielding the electrodes by lateral movement [12–14]. Other designs have employed vertical movement shutters [15,16]. In Ref. [17], the shutter and electrodes are on the same plane, with the moving shutter varying its shielding of the fringing electric field around the electrodes.

There are mainly three types of actuators applied in MEFMs to drive the shutter, thermal, piezoelectric and electrostatic. Thermal actuators can provide high driving force and large displacement [13–15]. In 2009, Wijeweera et al. demonstrated the first MEFM to measure the electric field measurement below an HVDC transmission line. Thermal actuators were applied to provide sufficient displacement for the shutter to cover the 14 μm wide sensing electrodes. It demonstrated a resolution of 42 V/m [13]. PZT actuators can provide high force and high switching speed as well. In 2013, Ghionea et al. using PZT actuator implement an ac electric field sensor which can detect 0.38 V/m/rt Hz in vacuum [16]. Electrostatic actuators have fast switching speed and low power consumption. In 2011, Yang et al. presented an electrostatic comb driven MEFM and achieve a resolution of 40 V/m for dc electric field measurement [17].

A significant issue with existing MEFM designs is that the shutter can be displaced towards the electric field source, in the presence of large fields. This affects the sensitivity of the MEFM, leading to inaccurate measurements, since the induced charge on MEFM electrodes is very sensitive to the gap between the shielding shutter and the underlying sense electrodes.

In recent years, some other types of micromachined electric field sensor have been reported. In 2008, Kobayashi et al. [18] presented a micromachined vertical vibration induction probe. The probe is installed close to the electrified body, and induced charge is generated with the vibration of the probe. In 2005, Roncin et al. [19] reported electrostatic force deflected membrane supported by micro-springs. This type of sensor is immune to the shutter displacement issue of MEFM sensors when in the presence of large electric fields. The displacement of the membrane is interrogated by a laser motion monitor system. It achieved electric field unmodulated measurement resolution of 5 kV/m for dc electric field and 0.3 V/m for ac electric field modulated measurement. In 2015, Huang et al. [21] presented a piezoelectric cantilever based ac electric filed sensor. It used a charged electret material coating to provide a fixed dc bias to the cantilever, and achieved a sensitivity of 0.84 mV/(kV/m).

This paper presents a micromachined electric field sensor for power utility applications. The sensor employs a biased sensing membrane that is displaced by the incident electric field. Compared to the work of Ref. [19] which used copper metal micro-springs, the sensor in this work is fabricated using an SOI wafer process. The SOI process provides precise control of the thickness of the membrane and micro-springs, and mitigates the stress issues which were a concern in [19]. Stress mitigation resulted in more predictable membrane mechanical characteristics. The SOI process additionally allowed for smaller and thinner membrane (20% the surface area, and 6 times thinner) for lower mass and stiffer micro-springs, providing higher natural frequency. This enables measurement higher frequency ac electric fields. Therefore, making the new sensor more applicable to industry for measurement of ac field and harmonics above 60 Hz. Further improvements over [19] include integration of the sensor with a compact laser position monitoring system, and usage of variable sensing membrane bias to provide adjustable sensor sensitivity. The sensor of this paper demonstrates superior resolution and sensitivity, for both ac and dc electric field measurement, and demonstrated the measurement of electric fields under a moc-transmission line.

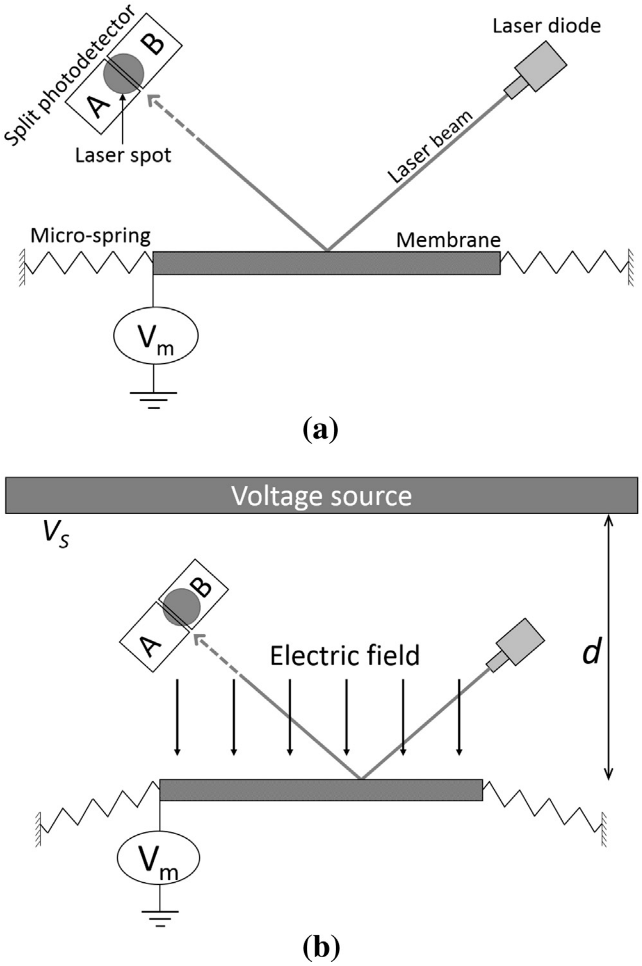

Fig. 1. Sensor working principle. (a) Shows the case when no external electric field is present. (b) Shows the case with an external electric field caused by voltage V_S.

2. Sensor design

Fig. 1 illustrates the working principle of this sensor. The mechanism consists of a membrane mirror suspended by a set of micro-springs, which will be displaced vertically under the influence of the electric field being measured (from source V_S). The vertical displacement of the membrane is indicative of the electric field strength and is measured using a laser position sensor. With no external electric field, the laser beam reflected by membrane falls on the center of the split photodetector as indicated on Fig. 1a. When the membrane is displaced by an incident electric field (Fig. 1b), the laser spot moves on the photodetector surface, giving an indication of the incident electric field. The difference between the output currents of the photodetectors A and B is used as the sensing signal.

A photograph of the micromachined membrane is shown in Fig. 2. The square membrane measures 1.15 mm × 1.15 mm, and each supporting micro-spring segment has length 1000 μm and width 20 μm. The membrane and micro-springs are fabricated from single crystal silicon with a 5 μm thickness. The structure is