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Single ended capacitive self-sensing system for comb drives driven *XY* nanopositioners

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ABSTRACT

This paper presents the implementation of a system to capacitively self-sense the position of a comb drive based MEMS *XY* nanopositioner from a single common node. The nanopositioner was fabricated using the multi-users PolyMUMPs process, on which comb capacitors fringe fields are large and out of plane forces cause considerable deflection. An extensive analysis of the comb-drive capacitance including the levitation effects and its correlation to the measurements is presented. Each axis is independently measured using frequency division multiplexing (FDM) techniques. Taking advantage of the symmetry of the nanopositioner itself, the sensitivity is doubled while eliminating the intrinsic capacitance of the device. The electrical measured noise is 2.5 aF/$\sqrt{\text{Hz}}$, for a sensing voltage $V_{sen} = 3V_{rms}$ and $f_{sen} = 150$ kHz, which is equivalent to 1.1 nm/$\sqrt{\text{Hz}}$ lateral displacement noise. This scheme can also be extended to N-degree of freedom nanopositioners.

1. Introduction

MEMS based nanopositioners have become very attractive for high precision nanopositioning systems such as STM [1], AFM [2], aligning of optical elements [3], nano-manipulation [4,5] and probe based high density data storage [6] because of their low power consumption, fast dynamic response and their possibility for large scale fabrication.

There are two commonly used driving systems for MEMS nanopositioners [2]: electrostatic and electro-thermal. In both cases, displacement in the order of tens of microns can be achieved [7–9]. For electrostatic actuation comb drive devices are typically used. The advantages of this type of actuation are the very low power consumption (in the order of μW) and fast dynamic response that can be achieved with them. On the other hand, electrothermal actuators (V-beam actuators, also called Chevron-type actuators; and hot arm thermal actuators) can generate significantly more force at low actuation voltages with the cost of significantly higher power consumption (in the order of mW).

A comb drive device can be represented electrically as a variable capacitor and electromechanically they can be used as actuator or as sensors. For nanopositioning, it is typical to use two comb drives mechanically and electrically connected where one generates the mechanical displacement, while the other one sense the displacement [7,10,11]. However, it has been demonstrated that comb drive devices can work as actuators for nanopositioning while simultaneously sensing its own displacement [12,13].

In general, for the capacitive read-out circuit differential configuration is used to reduce common-mode noise and parasitic effects. Also, for multi-electrode capacitive system, techniques such as frequency division multiplexing (FDM) or time division multiplexing (TDM) can be used to sense each differential output. On the one hand, TDM is attractive because allows to implement the read-out

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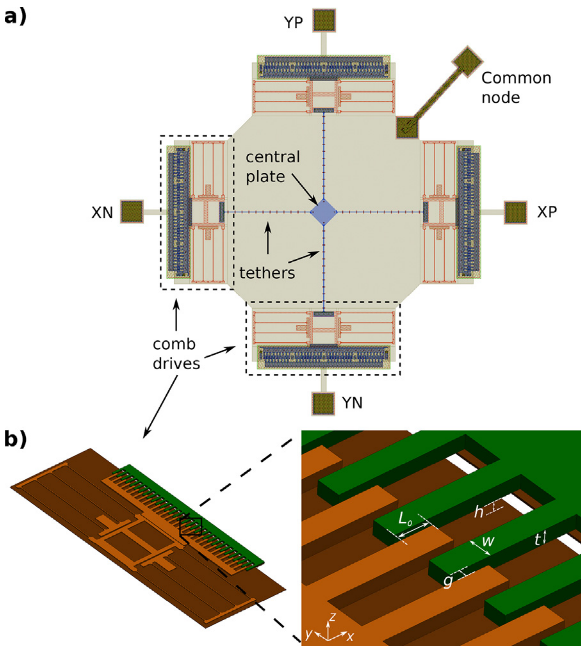

Fig. 1. (a) MEMS comb drive actuated nanopositioner. The central plate can be moved on the plane of the substrate actuated by the four comb drives connected to it through the tethers. (b) 3D representation of comb drive device. The zoom in the overlapped area of the combs shows its typical dimensions.

system using standard logic circuits [14], but has some limitations, e.g. excessive crosstalk, each sensor is measured sequentially, considerable increasing of noise due to the switching circuits. On the other hand, FDM can be implemented purely with analog circuits which can lead to better noise and crosstalk reduction and also allows parallel measurement of the array sensors [15].

In this paper, FDM technique is used to capacitively self-sense the displacement on a MEMS comb drive driven *XY* nanopositioners for both directions (*X* and *Y*) from a single common-node. A single readout circuit and a lock-in amplifier can be used to sense de displacement along either axis by simply switching the reference channel to the excitation frequency of the axis. This approach can be extrapolated to N-degrees of freedom.

A capacitance analysis for thin comb drive devices where, levitation and fringe field effect are considerable is performed to validate the experimental results. The discrepancy between experimental data and the model obtained is less than 2%. The measured capacitance noise is 2.5 aF/$\sqrt{\text{Hz}}$, for a sensing voltage $V_{sen} = 3V_{rms}$ and $f_{sen} = 150$ kHz. This result can be improved by increasing the sensing frequency up to 2 MHz which is the upper bandwidth limit of the circuit implemented.

2. Nanopositioner design

The device evaluated in this work was built using the PolyMUMPs multi-user process [16] provided by MEMSCAP. This process offers the possibility to design MEMS devices using three layers of highly doped poly-silicon and a single metal layer. The conductive substrate is isolated from the three layers by a 0.6 μm thick silicon nitride layer. The final gold layer is used to form high quality electrical connection to the MEMS.

The nanopositioner consists on a central plate suspended over the substrate by tethers that are mechanically and electrically connected to four identical comb drive actuators as shown in Fig. 1(a). The central plate can move in the plane of the substrate driven by the comb drive actuators. Opposite comb drives form a pull–pull type configuration to drive the central plate in one direction (e.g. *X* axis) and the additional set of comb drives move it in the orthogonal direction (e.g. *Y* axis). Each direction is divided in positive (P) and negative (N) respect to the initial condition of all four comb drives non-actuated (e.g. Y_P means the plate moving in *Y* direction towards the positive (P) way).

The spring constant of the tethers contribute about 10% of the spring constant in the transverse axis.

3. Comb drive actuator behavior

A comb drive is made up of two parts, an array of fixed fingers anchored to the substrate and another array of mobile interdigitated fingers suspended by springs. The fingers of width w and thickness t are separated by a gap g and overlapped by an initial length L_0 as is shown in Fig. 1(b). The comb drive behaves as an actuator when a bias voltage V_{act} (actuation voltage) is applied between the mobile and the fixed combs. The mobile structure is electrostatically attracted to the fixed comb and as result the overlap between the mobile and the fixed fingers L_0 increases to $L_0 + r$. Where r is the displacement intended to be use for nanopositioning proposes, referred to as *lateral displacement* and can be calculated as:

$$r = \frac{1}{2k_r}\frac{dC}{dr}V_{act}^2 = \delta_r V_{act}^2 \quad (1)$$

with k_r the spring constant in the r direction (which is a combination of the two folded flexural springs constants in r direction and the orthogonal tethers and flexural springs constants), C the total capacitance of the actuated comb drive and δ_r the lateral displacement electromechanical coupling coefficient.

Typically, in thin film comb drives (i.e. when $g \sim t$) as the fabricated using PolyMUMPs process, a grounding plane shorted electrically to the moving structure is placed underneath all the fingers to avoid unwanted charge accumulation in the substrate or a floating potential which could adversely affect the stability of the electromechanical response [17]. Secondary effects of having a grounded plane beneath the fingers are: (1) the reduction of the lateral displacement electromechanical coupling from δ_r to δ_r'; and (2) an asymmetry of the electric field in the overlapped mobile and fixed fingers area that induces a force normal to the plane of the substrate and causes to the mobile structure to levitate.

This out-of-plane/vertical displacement (levitation) can be calculated using the following equations [18]:

$$z = \frac{\delta_z\left(1+\frac{r}{L_0}\right)V_{act}^2}{1+\frac{\delta_z}{z_m}\left(1+\frac{r}{L_0}\right)V_{act}^2} \quad (2)$$

with z_m the asymptotic value of levitation, δ_z the vertical electromechanical coupling coefficient and the factor $\left(1+\frac{r}{L_0}\right)$ represents the contribution of lateral displacement to the levitation. Thus, levitation depends on lateral displacement. On the other hand, it can be demonstrated that lateral displacement is also levitation dependent (see appendix), then lateral displacement can be calculated as:

$$r = \delta_r'(1+\theta z)V_{act}^2 \quad (3)$$

where δ_r' is the electromechanical coupling coefficient for a comb drive with grounded plane underneath the fingers, and θ a factor that computes the influence of levitation over lateral displacement.

If necessary, levitation can be reduced/controlled as described in Refs. [18–20] or by pulling all four combs simultaneously at a voltage higher than 30 V, that is the voltage needed to reach the maximum levitation.