Sensors and Actuators A 222 (2015) 15–23

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

A MEMS linear accelerator for levitated micro-objects

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ARTICLE INFO

Article history:
Received 22 April 2013
Received in revised form 29 October 2014
Accepted 15 November 2014
Available online 22 November 2014

Keywords:
Microactuators
Linear accelerator
Micro-injector
Electromagnetic levitation
Electrostatic propulsion

ABSTRACT

In this work, the design, micro-fabrication, and characterization steps of a contactless linear accelerator is presented. The proposed design in principle can levitate conductive micro-objects and accelerate or move them over a predefined trajectory. The levitation is realized using electromagnetic induction generated by a changing AC field whereas the propulsion is achieved through electrostatic forces from a controlled DC source. This is the first time in literature that such a hybrid design is used to accomplish this idea. It has been experimentally shown that the proposed design can levitate 1 mm × 1 mm sized and 7 μm thick micro-objects to a maximum height of 75 μm and propel them forward continuously at a maximum average forward velocity of 3.6 mm/s.

1. Introduction

Following the recent advances in the microsystems technology, high-performance micro-inertial actuators and sensors can now be fabricated using standard fabrication methods and thus are widely available in a range of specifications. Although being easily accessible, the performance of such devices is still limited by a number of constraining factors such as proof mass weight, spring constant, and feature size. Among these factors, one important physical limitation is that the sensing or actuating element that is the proof mass, is constrained by a suspension structure acting as a mechanical spring. This limitation can degrade the overall performance of these devices such as sensitivity or output force, or restrict the motion range of an actuator. One way to overcome such limitation is to use other means to support the proof mass rather than using physical connections. For this purpose, in various studies so far, the sensing or the actuation element was supported through levitation using electromagnetic and electrostatic levitation techniques. Some applications examples used for this purpose were contactless micro-motors, gyroscopes, and micro-bearings.

This study presents a novel micro-linear manipulator, which can levitate and accelerate conductive micro-objects and extends the preliminary results outlined in [1]. Previously, Shearwood et al. [2] demonstrated a levitated and rotating gyroscope. In their work, the design featured a circular aluminum track over which an aluminum rotor was levitated and rotated by electromagnetic (EM) induction and a rotating EM field, respectively. The levitated rotor was constraint by stabilizing EM forces that were generated by a planar metal loop acting as stability coil. In a related later study by Wu et al. [3], similar techniques were used to levitate, rotate, and stabilize a rotor for the application of a gyroscope. In another study by Murakoshi et al. [4], a levitated, ring shaped rotational gyroscope and accelerometer is presented. Electrostatic (ES) forces were used to levitate, stabilize, and rotate the rotor. Different from the previous two studies, a closed-loop force feedback technique is required for the position control of the rotor. In addition to the work discussed so far, similar EM and ES levitation and control techniques were presented for other applications as well such as micro-motors and micro-bearings [5–9]. Besides these, Kumar et al. demonstrated a levitated linear actuator where a 24 mm × 24 mm × 180 μm sized object was first levitated by ES forces. Then, the levitated object was moved forward and backwards by a stroke of 200 μm by switching the drive electrodes on and off, respectively [10]. Another type of levitated linear actuator was presented by Jin et al. [11]. In this work, an 8-in Si wafer was levitated by electrostatic forces and propelled along a linear path by sequentially energizing pairs of electrodes. This was a macro scale application, which was mainly developed for contactless transfer of silicon wafers. Different from active levitation strategies, Liu et al. [12] presented a levitated diamagnetic rotor that was levitated by NdFeB magnets. The levitated rotor was then actuated by a rotating ES field similar to an axial variable-capacitance motor.

A number of techniques have been demonstrated to levitate and manipulate micro-objects in various applications. However,

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http://dx.doi.org/10.1016/j.sna.2014.11.008
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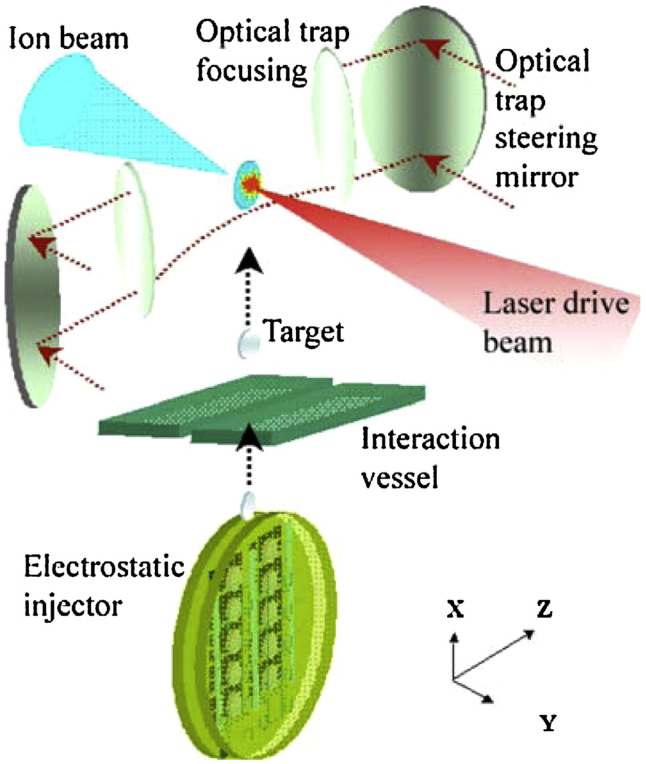

Fig. 1. Schematic representation of the application where the proposed manipulator is intended to be used.

in most of these applications, circular micro-objects were manipulated and most importantly they did not have any *continuous propulsion* capability along a linear trajectory. In this work, the proposed design is capable of both levitating and accelerating micro-objects along a predefined path. It combines two different techniques to realize this: electromagnetic induction for levitation and electrostatic forces for propulsion. It can be used in a number of applications like contactless acceleration and positioning of micro-objects, injection systems, and contactless inertial sensors. The design presented here was specifically developed for a target injection and trapping application. Fig. 1 is a schematic representation of the final application where the proposed device is aimed to be used. It is composed of a vacuum interaction vessel and an electrostatic injector system (note that the actual levitation and injection system design proposed in this work is schematically different than the "electrostatic injector" shown in this figure). There is an optical trapping system [13], a laser drive beam, and measurement instruments inside the interaction vessel. The micro-object of interest is levitated and accelerated inside the vacuum interaction vessel using the design presented in this work after which it is trapped by the optical trapping system. The levitated object is then moved to an optimal position where it is shot by a laser beam at different power levels and intensities and the resulting ion-beam radiation is investigated. For this application, it is crucial that the micro-objects are suspended without any attachments as such connections would perturb the ion-beam production mechanism. The investigation of resulting ion-beam production from different materials has importance in many fields such as:

- medicine (cancer treatment through laser energized protons and ions at a much lower cost),
- industry (in situ radiography, diagnostics, semiconductor fabrication),
- science (research in synchronized beam production),

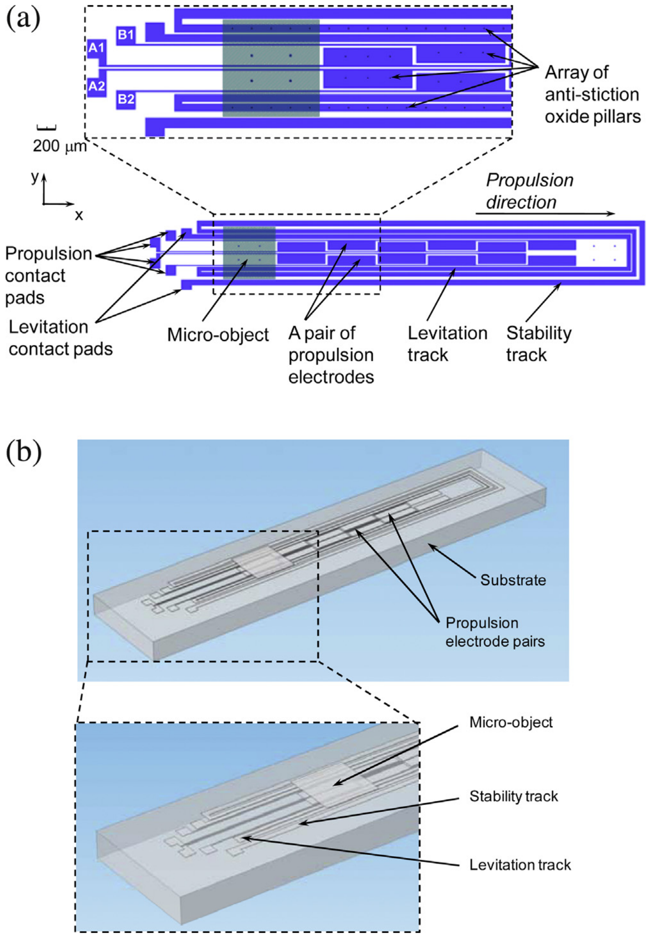

Fig. 2. (a) Schematic of the proposed micro-linear manipulator that is composed of levitation and stability tracks and forward propulsion electrodes. (b) Isometric view of the design.

- security (image detection of hidden materials and objects using tomography).

To the best of authors' knowledge, this is the first time in literature that a combined levitation and acceleration design concept is proposed and demonstrated to work. The paper is organized as follows: Section 2 describes the modeling, and simulation, Section 3 discusses the fabrication steps of the design, and finally Section 4 presents the experimental results of the work together with actual measurement data for levitation and propulsion.

2. Design

Fig. 2a shows a schematic top view of the device prototype comprising an outer rectangular, conductive aluminum loop and a series of paired rectangular aluminum electrodes inside this loop. Fig. 2b is an isometric view of the design. The micro-object is levitated by electromagnetic induction by applying an AC signal (10–55 MHz) to the electrical pads of the rectangular loop. The loop consists of an inner (levitation) and an outer (stability) track. The inner track induces a levitation force on the micro-object that is defined by the Lorentz force:

$$\vec{F} = \vec{J} \times \vec{B} \tag{1}$$

where F is the levitation force exerted on the object, B is the magnetic field density induced by the alternative current in the inner track and J is the induced eddy current density in the object by the magnetic field. It would ideally be beneficial to derive a detailed