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Double stage FPCB scanning micromirror for laser line generator☆

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ABSTRACT

This paper presents a laser line generator consisting of an electrostatic scanning micromirror utilizing a Double-Stage Flexible Printed Circuit Board (DS-FPCB). It consists of two stages with the rotating electrode in the 1st stage, and the mirror plate in the 2nd stage. Due to both rotating electrode being much closer to the rotational axis and the rotational amplification effect between the two stages, the DS-FPCB micromirror can have a 90% higher maximum rotation angle, in comparison to previously developed single stage FPCB micromirrors, while retaining benefits of low cost (a few dollars) and high surface quality (high flatness, radius of curvature (ROC) > 10 m, good roughness of nanometers). The DS-FPCB micromirror is modeled and prototypes are fabricated and tested, achieving a 3.25° optical rotation at 100 V (sinusoidal wave driving signal) and 10.87° at 150 V (square wave driving signal), both at 117 Hz. A laser line generator based on the DS-FPCB micromirror is developed and tested, whose laser power density along the line is uniform and independent on the projection distance, while the conventional laser line generator's laser power density varies along the laser line and is highly dependent on the projection distance.

1. Introduction

MEMS (Microelectromechanical Systems) micromirrors have been developed since 1990s and successfully used in displays [1–5], optical switches [6] and medical devices [7] due to its advantages such as small size, high integration, high reliability and low potential cost. Micromirror based laser scanners have a broad range of applications [8,9], such as barcode reading [10], Light Detection and Ranging (LiDAR) [11], depth sensing using structured light [12], and bio imaging [13,14] etc. A MEMS micromirror could be driven via electrostatic [3,15,16], thermal [17,18], magnetic [19–22] and piezoelectric [23–25] methods. Micromirror based laser scanners require a large aperture (millimeters) and high surface quality of the mirror plate, e.g., high flatness, Radius of Curvature (ROC) > meters with roughness of nanometers. However, this type of MEMS micromirror has a high fabrication cost, e.g., $10's because the fabrication process involves both expensive micromachining and low yield bonding of highly fragile released micro actuators with a mirror plate [26–29]. Consequently, MEMS micromirror based laser scanners are not widely adopted in the market thus far. Flexible printed circuit board (FPCB) micromirrors [30,31] were presented, which can achieve large aperture and high surface quality with very low cost. This technology uses FPCB process to fabricate the flexure and driving parts, which are then bonded with a mirror plate fabricated by dicing a polished silicon wafer coated with an aluminum film, to achieve large aperture, high surface quality and low cost (e.g., < 1 $ for high volume and few dollars for medium volume). The FPCB micromirror is an electrostatic parallel plate actuator driven by an electrostatic force. Therefore, when comparing with traditional parallel plate electrostatic MEMS micromirrors, there is no difference in terms of power consumption and driving voltage. Because of the material used (normally polyimide) is of low elastic modulus, the resonant frequency is lower. Its outstanding advantages lie in the large aperture (a few millimeters), high flatness (ROC > 10 m) and low cost (a few dollars) while traditional MEMS micromirror is of 10–100's µm in aperture, ROC of centimeters ~ 1 m (depending on the fabrication technology) and 10s dollars in cost (for mass production). These FPCB micromirrors have small maximum rotation angles, e.g., < 6°, which are enough for the applications of availability indication [30] and as a laser pattern pointer [31]. But it is not enough for some laser scanner applications such as the laser line generator. Usually a scanning laser line is used for measurement, e.g., LiDAR or depth sensing, which requires a larger rotation angle (10's degrees) to cover larger areas with one laser line generator.

The laser line generator projects a straight laser line with uniform laser power density at various locations on the line, which could be used for alignment, positioning, barcode scanning, depth sensing, etc. The conventional laser line generator based on cylindrical lens or a Powell lens has a fixed fan angle. Consequently, the length of the laser

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line and laser power density are highly dependent on the projection distance. If the distance is far, the line generated becomes very long and the laser power density becomes too low to be useful. Moreover, its laser power density varies along the same line, i.e., higher in the middle of laser line and lower at the edges. An SOIMUMPs micromirror based laser line generator [32] was developed to solve this limitations, which can project a laser line with a constant laser power density and adjustable fan angle. However, the projected laser line becomes too thick when the distance is over 3 m because of the poor mirror surface quality, e.g., ROC = 9.52 cm. The laser line generator based on the FPCB micromirror can overcome this problem due to its high flatness of mirror plate.

This paper presents a Double Stage FPCB micromirror (named as DS-FPCB micromirror hereafter). It consists of two stages with the rotating electrode in the 1st stage and the mirror plate in the 2nd stage. As a result of the rotating electrode being much closer to the rotational axis and the rotational amplification effect between two stages, the DS-FPCB micromirror can have a much higher maximum rotation angle, in comparison to previously developed single stage FPCB micromirrors. This is achieved while retaining benefits of a large aperture, low cost and high surface quality. This DS-FPCB micromirror concept was first introduced by the authors in the conference paper [33] with simple and rough modeling, as well as basic prototyping of the micromirror. In this paper, detailed and accurate modeling is performed, such as the coupling-field transient simulation considering the varying electrostatic force instead of assuming a magnitude fixed sinusoidal force. In addition, a laser liner generator based on the DS-FPCB micromirror is built, tested and analyzed.

Section 2 introduces the working principle of the DS-FPCB micromirror and laser line generator. Section 3 presents the modeling and simulations. Section 4 describes the prototypes and testing of the micromirror. Section 5 presents the prototype and testing of the laser line generator. The conclusions are summarized in Section 6.

2. DS-FPCB micromirror and laser line generator

2.1. The DS-FPCB micromirror

Fig. 1 shows the structure of DS-FPCB micromirror including the rotating plate and two fixed plates, which is an electrostatic parallel plate actuator driven by electrostatic force. The rotating plate has two stages as shown in Fig. 1(a), i.e., the 1st stage is the rotating electrode with the torsion beam (Beam 1) connected to anchors, the 2nd stage is the mirror plate with beams (Beam 2) connected to the 1st stage. The fixed plates as shown in Fig. 1(b) are above and under the rotating plate, e.g., the upper and lower fixed plates. The rotating electrode is a copper layer in the rotating plate, which can be applied with a driving voltage and pulled up or down by the electrostatic force. The copper layer in the rotating plate is the upper/lower fixed electrode used to apply the driving voltage to generate the electrostatic force. The upper and lower gap spacers are used to form 0.2 mm gaps above and underneath the rotating electrode. The spacers are made of the FR4 PCB stiffener, which are available in the standard FPCB fabrication process. Although a larger gap will result in larger maximum rotation angle, it would require a higher driving voltage. It is easy to build a driving circuit within 200 V driving voltage; otherwise the higher driving cost will diminish the advantage of the low cost micromirror. Based on the experimental and simulation results of the previous two FPCB micromirrors, 0.2 mm gap is selected to keep the driving voltage lower than 200 V. A 2 mm × 2 mm silicon mirror plate is fabricated by dicing a polished 120 μm thick silicon wafer with a 100 nm aluminum coating. It is bonded on top of the mirror holder in the 2nd stage as shown in Fig. 1(c). The reflectivity of the aluminum coated mirror can reach over 85% for a visible laser light. After bonding the diced mirror on top of the mirror holder, it will not cause initial tilting with proper bonding to keep the beams in elastic deformation.

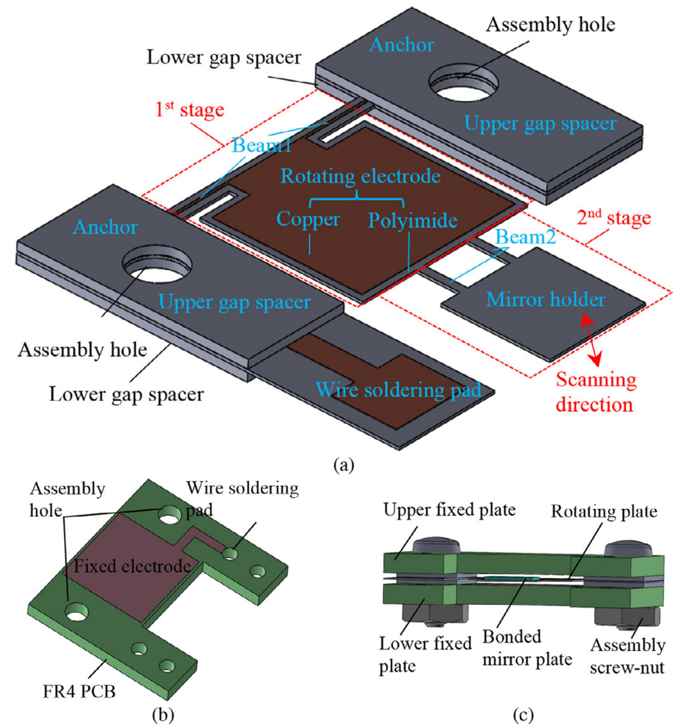

Fig. 1. Structure of DS-FPCB micromirror. (a) Rotating plate. (b) FR4 PCB fixed upper or lower plate. (c) Assembled DS-FPCB micromirror.

The rotating plate including the rotating electrode, the mirror holder, beam 1 and beam 2 are fabricated using the standard FPCB process, which are multilayer structures, i.e., a polyimide base layer and a copper layer covered with a thin isolation layer, except for the wire soldering pad area. The fixed plates are made of FR4 PCB. The copper layers of the rotating electrode and fixed electrodes are covered with thin isolation layers to prevent short circuiting in case of touching.

The DS-FPCB micromirror has a larger maximum rotation angle in comparison to previously developed FPCB micromirrors [30,31] (referred to as FPCB micromirror 1 and FPCB micromirror 2 in this paper) because:

(1) The gap height and distance of the rotating electrode's tip to the rotational axis determine the physical rotation limit, 73.1% of which is the maximum oscillation angle due to the "pull-in" effect [34]. Since the DS-FPCB micromirror has the rotating electrode tip much closer to the rotational axis than that in the previous FPCB micromirrors as shown in Fig. 2, even with the similar rotating electrode length, its maximum rotation angle is much higher. The maximum mechanical rotation angle for only lower direction can be calculated according to Eq. (1).

$$\theta_{Rotation} = 0.731*arctan(g/d) \quad (1)$$

where g is the gap between the rotation and fixed electrode and d is the distance from the fixed electrode's edge to the rotational axis. Considering rotation in both upper and lower directions, the optical rotation angle is double of the mechanical rotation angle, the maximum optical rotation angle will be 4 times of $\theta_{Rotation}$. For example, gaps are 0.2 mm for all three designs, the maximum rotation angles for the rotating electrode are 5.88° for the previous two designs and 8.13° for the DS-FPCB micromirror according to the dimensions as shown in Fig. 2.

(2) In the DS-FPCB micromirror, the 2nd stage (mirror plate)'s rotation is higher than that of the 1st stage (the rotating electrode) due to the rotational amplification effect caused by beams connecting the 1st and 2nd stages. This amplification is about 1.58, as explained in