Micromachined Polarization Beam Splitter With Adjustable Leak Ratio for Optical Pickup

C. H. Tien and C. H. Hung

***Abstract*—In this letter, we propose the optomechanical design and fabrication of a novel batched-processed polarization beam splitter (PBS) with an adjustable leak ratio for optical recording applications. The micro-PBS was fabricated by a 410-nm low stress silicon nitride Si_3N_4 membrane integrated with a bimorph actuator. A dc drive voltage was applied to allow an adjustable leak ratio (0–0.24) with incident angle from 65° to 75° for operation in the different optical requirements (phase-change and magneto-optical disks) at $\lambda = 633$ nm. The characteristics of the fabricated PBS are in close agreement with the theoretical calculations and confirm its feasibility.**

***Index Terms*—Integrated optics, microelectromechanical systems (MEMS), optical components, optical device fabrication.**

I. INTRODUCTION

THE micromachining, or microelectromechanical systems (MEMS) technology has opened up many new possibilities for the feature of miniaturization and integration [1], [2]. In particular, optics is an ideal target since a photon has no mass and is much easier to actuate than other macroscale objects. This unique feature leads to a variety of applications such as single-chip free-space optical disk pickups [3] and micro-interferometric bench [4]. Within these multiple applications, polarization beam splitters (PBSs), important optical devices to separate the orthogonal p and s-polarized components of light, play a key role when the states of polarization are concerned in an optical system. Most conventional PBSs made of birefringent crystals are subject to a bulky size; the MEMS-based approach provides a possible route to overcome this issue and allow its further application in a microscopic scale [5]. Taking an optical recording system as a target, a high-extinction-ratio PBS is required to operate in different optical requirements of various disk formats [6], as schematically shown in Fig. 1. In the forward path of magneto-optical (MO) operation, the incident beam is p-polarized and the PBS is adjusted to allow a large portion $(1-R_p)$ of incident beam to the medium. After being reflected from the MO medium, Kerr effect would lead to a cross-polarization factor that couple, somewhat, an amount of incident p-wave into the s-wave of the reflected light. In the return path, the PBS diverts the same fraction R_p and essentially all the s-polarized wave $(R_s \sim 1)$ to the detection as the readout signal. In general, the optimum fraction of leak ratio R_p/R_s depends on the sources of noise within the overall system [7]. For a differential detection scheme in a typical MO system, the typical leak ratio is about 0.2–0.3, where PBS is adjusted to reflect almost 100% of the s-polarized light and 20%–30% of the p-polarized light. On the other hand, while the system operates in phase change (PC) or other nonmagnetic media, the leak ratio of the PBS must change to zero to obtain the optimum signal. In this case, the combination of PBS and quarter-wave plate provides an optical circulation that passes almost 100% of the p-polarized laser $(R_p \sim 0)$ but redirects all reflected s-polarized $(R_s \sim 1)$ to the data or servo detectors. Although the surface micromachining free-space microoptical bench has been demonstrated in the literature, the function of adjustable polarization ratio and its optomechcnical consideration have never been reported to our knowledge. In this letter, we employed the thin-film optics, comb-shape external electrodes and post heat treatment to design, fabricate, and evaluate a unique batch-process PBS, which is able to achieve a high-reflectance reflector for s-polarization and, simultaneously, to achieve a partial p-reflectance varied from 0% to over 20% with some small range of incidence for different operations in the optical recording systems.

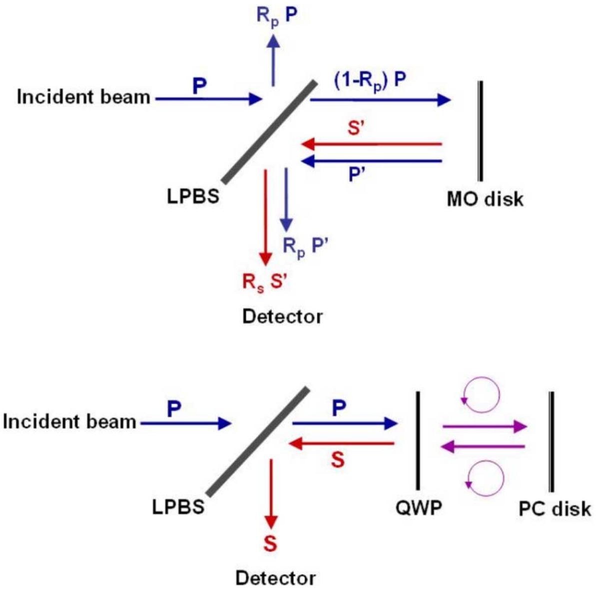

Fig. 1. Schematic PBS operation at MO and PC recording system.

II. OPTICAL DESIGN

In order to obtain the optimal performance for a thin-film PBS, the issue of material and the deposition method must

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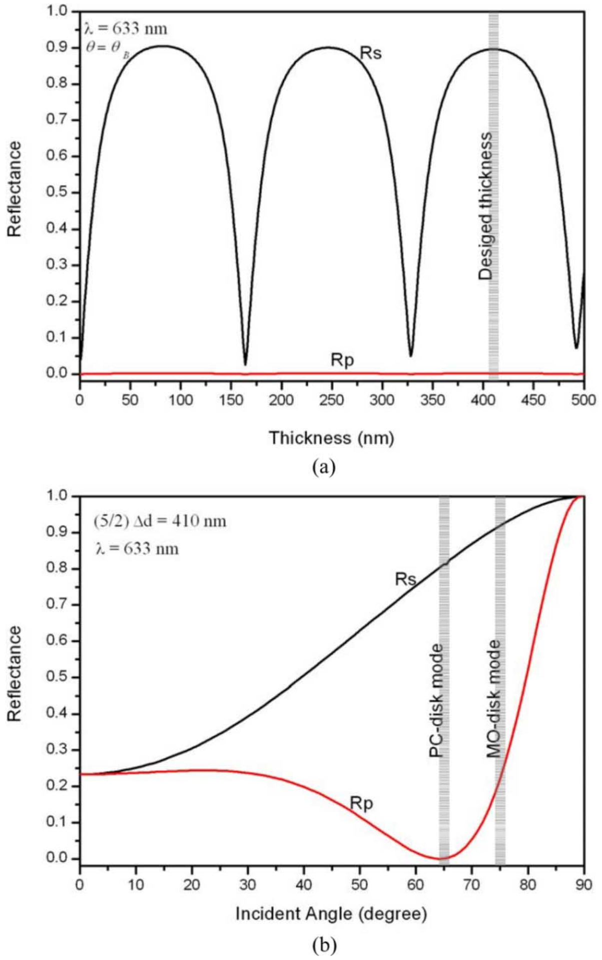

(a)

(b)

Fig. 2. (a) Calculated reflectance versus silicon nitride thickness at Brewster's incidence. (b) Calculated reflectance versus incident angles with 410-nm silicon nitride, where $R_p = 0, R_s = 0.8$ at Brewster incidence ($\theta = 65^\circ$) is operated for PC disk and $R_p = 0.27, R_s = 0.92$ at $\theta = 75^\circ$ is operated for MO disk.

be investigated first. In view of high transparency at red light ($\lambda = 633$ nm) and low residual stress below 50 Mpa, a silicon nitride membrane is an appropriate candidate as the PBS in terms of its optical quality and mechanical stability. Also, low-pressure chemical vapor deposition was adopted as the deposition method because its deposition condition is at fairly low temperatures, which can alleviate the thermally induced stress and decrease the risk of failure of cracking. The PBS utilizes the polarization-sensitive nature of the homogeneous dielectric layer to oblique incident light. For 633-nm light and a membrane of silicon nitride Si_3N_4 (refractive index $n = 2.13 + i0.0065$), our starting design for such thin-film PBS was to determine a proper thickness of the film under a specific incident condition. As is well known, when a collimated beam is incident on a thin film at its Brewster's angle, the p-polarized light will be totally transmitted, leaving the reflected light to be pure s-polarized light. Meanwhile, the transmitted light is still a mixture of s- and p-polarization, yet by choosing an adequate material in proper thickness, the reflectance for the s-wave could be tuned to a high level, leaving the transmitted light mostly p-polarization. Such high-extinction-ratio is appropriate for operation in the PC or other nonmagnetic media. Fig. 2(a) shows the calculated reflectance of a Si_3N_4 film,

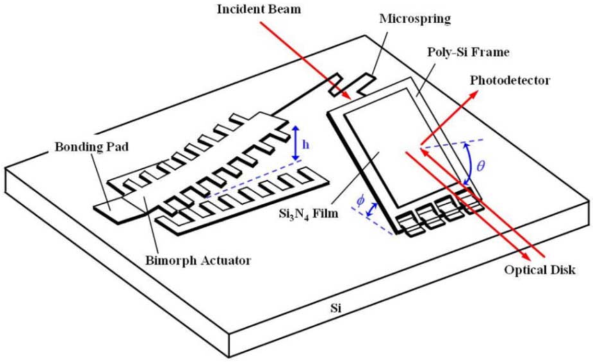

Fig. 3. Schematic configuration of the adjustable micro-PBS.

which is a periodic function of thickness at Brewster's angle ($\theta_B = 65^\circ$), where the period of thickness is calculated from $\triangle d = (\lambda 4n/\cos\theta_B)$. The maximum reflectance appears when the thickness satisfies $(m + 1/2)\triangle d (m = 0, 1, 2, \ldots)$. Here we designed Si_3N_4 thickness to be 410 nm (where $m = 2$) as a tradeoff in high transmittance accompanied with sufficient membrane strength. In this case, the maximum reflectance for s-polarization is about 80%; the value can be further increased by the structure of multiple stacking layers [8]. Alternatively, for the operation in MO media, the reflectance of p- and s-polarized light was switched to a value under another incident angle. Fig. 2(b) shows that the reflectance R_s and R_p curves exhibit different behavior with various incidences. The R_s could be kept over 80% and the R_p was varied from 0% to 20% within the operating angular range 65°–75°. Because the PBS was integrated with a bimorph actuator, we can adjust the extinction ratio by actuating the bimorph actuator accordingly.

III. ELEMENT FABRICATION

The adjustable PBS was fabricated using an MUMPs-like surface micromachining process, including two-layer Poly-Si, two-layer SiO_2, and one-layer low-stress Si_3N_4. The Si_3N_4 optical splitting membrane was deposited with SiH_2Cl_2–NH_3 ratio $= 5$ at 850 °C and 180 mTorr and patterned on the Poly-Si frame. In addition, we conducted a 2-h annealing to successfully reduce the stress of the Si_3N_4 from the original 267 MPa down to 44 MPa. Such a process is able to highly relieve the influence of the curvature upon the optical behavior of the PBS. Finally, a 140-nm-thick Cr and a 0.5-μm-thick Au were deposited on the cantilever to induce the internal stress. Upon releasing in hydrofluoric vapor to remove the SiO_2 layers at 40 °C, the cantilever beam curved upward to lift the PBS off the substrate. The schematic drawing of the optomechanical setup is shown in Fig. 3. The Si_3N_4 membrane attached to the silicon substrate with an initial oblique angle $\phi = 25^\circ$ was adopted as a beam splitter. This $650 \times 250\ \mu m^2$ Si_3N_4 membrane was bounded by a polysilicon frame. One edge of the polysilicon frame attached to the substrate was the axle of the movable membrane. The other end connected to the bimorph actuator through a microspring was lifted based on the concept of prestress comb-drive actuator (PCA) with different driven states [9]. This bimorph actuator was designed to provide a vertical force, which is able to pull down the lifted edge of the oblique film through the microspring. As the lifted edge moves vertically, the incident angle of light is varied from 65° (PC) to 75°

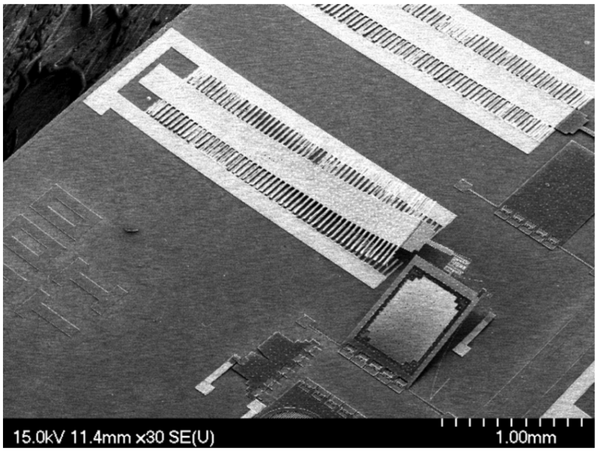

Fig. 4. Experimental result of the free-space micromachined adjustable PBS.

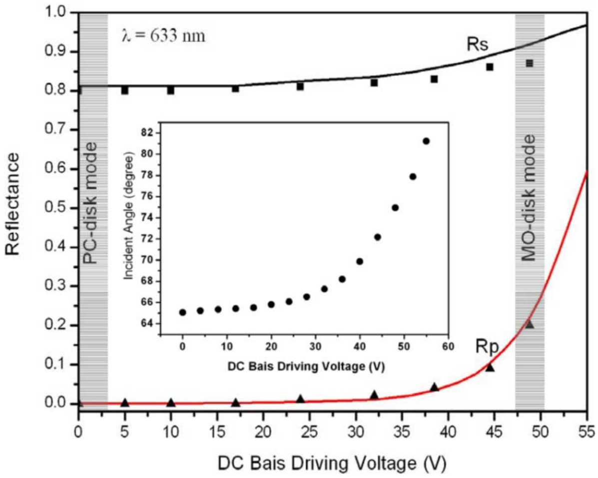

Fig. 5. Results of measured reflectance versus dc bias driving voltages, compared with calculated curves. PC-disk mode: $R_p/R_s = 0/0.8$ at 0 V. MO-disk mode: $R_p/R_s = 0.2/0.85$ at 48 V. Inset: the measured incident angle versus the applied dc voltages.

(MO) according to the different leak ratio requirements. The PCA consists of a bonding pad, a composite beam and a set of 86 comb fingers. One end of the composite beam was clamped to the bonding pad, while the other end connected to the polysilicon frame was elevated due to the residual stress between two deposited materials Cr-Au. An initial lift height $h = 380\ \mu$m corresponding to the oblique angle $\phi = 25°$ can be controlled by adjusting the residual stress of the composite beam by using a post heat treatment process [10]. When a voltage V is applied between the movable and fixed comb through the electrode, the movable beam can be pulled downward by the electrostatic force from the fringe effect. The electrostatic force is expressed as $F_E = (1/2) \cdot (\partial C/\partial z).V^2$, where C is the capacitor between combs, and z is the moving distance of composite beam. Therefore, the extinction ratio of the PBS switched between the states of MO and PC mode can be realized by actuating the bimorph actuator.

IV. MEASUREMENT AND RESULTS

Fig. 4 shows the scanning electron microscope photograph of the micro-PBS, where the snap-down voltage was set to zero. To measure the leak ratio of the micro-PBS, a 633-nm He–Ne laser was directed at the surface of the PBS device with different incident angles. A polarizer was used to adjust the polarization state of the light source. The transmitted and reflected beams from the test sample were then detected by the power meters, respectively. The measured incident angle was varied with different applied dc voltage, and the results were shown in the inset of Fig. 5. The initial working state subject to free snap-down force was used for PC medium, where R_s and R_p were measured to reach 80% and 0%, respectively. While the system is switched to MO operation, an external voltage of 48 V was applied to the PCA, attracting it to the ground substrate from the initial lift height. The reflectance R_s and R_p thus become 85% and 20%, respectively. Measured reflectance R_s and R_p versus under different driving voltage are plotted in Fig. 5. In each case, the theoretical expected curves are also shown (as dashed curves). The discrepancy between theory and experiment at higher operating voltage is due to the scattering losses from the surface roughness and the voltage drift during the operation. Nonetheless, the close agreement with the theoretical prediction still confirms the characteristics of the micro-PBS with adjustable leak ratio for PC and MO system, respectively.

V. SUMMARY

We have developed a MEMS-based micro-PBS with adjustable leak ratio for different requirements in the optical recording operation. The PBS has a 410-nm Si_3N_4 light splitting membrane actuated by a prestress comb drive using a two-layer polysilicon and one-layer low stress silicon nitride surface micromachining process. The applied voltage required for switching the PBS between PC and MO state is 0 and 48 V, respectively. In addition, under the driven voltage from 0 to 48 V, the leak ratio is able to be continuously varied in a range of 0–0.24, which opens an opportunity for state-of-the-art techniques to meet significant requirements of optical storage systems in a microscopic scale.

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