MONOLITHIC INTEGRATION OF BINARY-PHASE FRESNEL ZONE PLATE OBJECTIVES ON 2-AXIS SCANNING MICROMIRRORS FOR COMPACT MICROENDOSCOPES

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ABSTRACT

We demonstrated unique monolithic integration of Fresnel zone plate objective on 2-axis staggered vertical combdrive micromirror surface via direct patterning of reflective binary-phase-modulation elements on silicon. Need for focusing optics is thus obviated, simplifying microendoscope assembly and improving form factor. Micromirrors scanning $\pm 9^\circ$ (optical) about both axes are patterned with elliptical zones designed for 7mm (8mm) focal length and 20° (45°) off-axis 635-nm illumination using 635nm (1310nm) laser. Videos of samples acquired with $\sim 15\mu\text{m}$ lateral resolution over $1\text{mm} \times 0.35\text{mm}$ field of view at 5.0 frames/second using the device in a bench-top single-fiber laser-scanning confocal microscope confirm applicability of the device to microendoscopy.

INTRODUCTION

In vivo optical imaging is an important tool for medical diagnosis in situations where biopsy is difficult, and for image-guided microsurgery and photodynamic therapy [1]. Cellular-level imaging enables early detection of many diseases such as cancers, which can be crucial to effective treatment and patient survival chances [2]. Visualization in sensitive internal non-tubular human organs requires compact forward-imaging endoscopes, which have thus far proven to be difficult to assemble in small form factor, as opposed to sideways-imaging probes [3]. Microelectromechanical system (MEMS) technologies are uniquely positioned to provide distal beam deflection for image formation in microendoscopes. Vertical combdrive micromirrors have been shown to provide the large rotational torque, deflection angles and mirror surface quality for laser-scanned imaging systems [4]. However, catheter rigid length and outer diameter are mainly limited by focusing optics. Micromachined 3-D optics has been assembled into integrated free-space systems [5]. For multi-element systems, such as catheters, additional assembly becomes increasingly challenging and expensive. The present research addresses the above limitations by monolithically integrating a micromachined Fresnel zone plate objective directly on the surface of the micromirror via patterning of reflective binary-phase-modulation elements.

THEORY

Coherent illumination incident on the micromirror surface at an angle to the mirror normal can be concentrated at a wavelength-dependent focal distance by an Elliptical Zone Plate (EZF, Figure 1) designed according to equation (1):

$$\left(\frac{x}{a_n \cos \theta} \right)^2 + \left(\frac{y - b_n}{a_n} \right)^2 = 1, \text{ where}$$

$$a_n = \frac{\sqrt{n\lambda \left(f \cos^2 \theta + \frac{n\lambda}{4} \right)}}{\cos^2 \theta} \text{ and } b_n = \frac{n\lambda \sin \theta}{2 \cos^2 \theta} \quad (1)$$

Figure 1: Illustration of design parameters for scanning binary-phase reflective Elliptical Fresnel Zone Plate (EZF). θ is the off-axis illumination angle of wavelength λ , θ_s the micromirror scan angle, w and w_f are the incident and focused beam waists, and f is the focal length of the EZF with n zones.

θ is the off-axis illumination angle about the x -axis with respect to the micromirror normal, λ is the illumination wavelength, f is the focal distance, and a_n and $a_n \cos(\theta)$ are the semi-major and semi-minor axes of the elliptical boundary of the n^{th} zone of the EZP. Degradation in focal spot size (indicated as w_f in Figure 1) due to changing illumination angle θ (by micromirror rotation) and wavelength are negligible for optical path difference deviation at the zone boundaries of less than $\lambda/4$ from nominal value [6, 7]. Therefore, the EZP can be fabricated for required focal spot size under maximum rotation angle to prevent aberrations using the following design constraints –

$$\text{Spherical Aberration:} \quad n \approx \sqrt{2f / \lambda} \quad (2)$$

$$\text{Chromatic Aberration:} \quad n \approx \lambda / \Delta \lambda \quad (3)$$

$$\text{Off-Axis Aberration:} \quad \alpha \approx (3n)^{-1/2} \text{ (for small } n) \quad (4)$$

These conditions restrict the maximum number of EZP zones and micromirror scan angle (indicated as θ_s in Figure 1), therefore determining the number of resolvable points in the image or the “numerical aperture” of the EZP. Variation of focal distance with wavelength may provide a new mechanism for 3-D imaging through axial scan [8].

FABRICATION

The micromirror is actuated by staggered vertical comb drives fabricated by a comb self-alignment process in bonded double-SOI wafers [9, 10]. Coarse features of the stator are etched by Deep Reactive Ion Etching (DRIE) into $25\mu\text{m}$ thick SOI $\langle 100 \rangle$ device

Figure 2: Device fabrication process sequence. (a) DRIE of coarse features in to SOI device layer. (b) Bond oxidized wafer, grind/polish. (c) Pattern binary-phase modulation elements of zone plate into micromirror surface. (d) Chemical vapor deposit silicon dioxide and pattern with exact micromirror features. (e) DRIE-Oxide RIE-DRIE sequence to create self-aligned actuators. (f) Backside DRIE to release micromirror, and oxide RIE on both sides to remove protective oxide.

layer (Figure 2). An oxidized <100> wafer is fusion bonded on top of the patterned wafer, and ground down to 25 μ m thickness with <50nm surface roughness to form the micromirror surface. Features of the elliptical zone plate objectives are patterned on the surface to quarter-wavelength depth. Exact features of the actuators, aligned to the lower layer features, are etched into deposited silicon dioxide. DRIE-oxide RIE-DRIE etching sequence forms the self-aligned. Backside substrate DRIE and oxide RIE on both sides releases the mirror and removes remaining protective oxide. Scanning electron micrographs of the fabricated device are presented in Figure 3.

DEVICE CHARACTERIZATION

Scanning EZPs designed for 635nm (1310nm) wavelength with focal lengths of 7mm (8mm) and off-axis illumination angles of 20° (45°) were fabricated on micromirrors of size 500 μ m $\times$ 700 μ m. Two-axis beam scanning is obtained by mounting the micromirror by torsion rods within a gimbal, which is suspended by torsion rods aligned in the orthogonal direction. Rotation about each axis is driven by two sets of staggered vertical comb drives. This configuration leads to two-axis angular scanning about a single pivot point at the center of the micromirror, which reduces optical field distortions.

Frequency response characteristics (Figure 4a) of the micromirror were tested by applying voltage of 20.0+20.0sin(ωt) volts and varying the sinusoidal frequency. The micromirror

Figure 3: SEM images of the fabricated device. (a) Top view showing the EZP, vertical comb drives, torsion springs, and bond pads for electrical connection. (b) Backside view showing DRIE trench with vertical sidewalls to release the scanning micromirror. (c) Close-in view of vertical combdrive.

Figure 4: Micromirror operating characteristics. (a) Frequency response characteristics (Applied voltage= 20.0 + 20.0sin(αt) V). (b) Static deflection characteristics on driving one comb bank on each axis.

exhibits resonant out-of-plane rotation at 2280Hz and 383Hz for the inner and outer axes respectively. The static voltage deflection characteristics (Figure 4b) were determined by applying a DC voltage to one comb drive on each axis. Static voltage deflection of $\sim 9^\circ$ (optical) was measured on application of 110 volts on both axes. Raster scan pattern was used for point-by-point image formation, employing resonant frequency operation of the inner axis for fast line scan, and non-resonant operation of outer-axis for frame scan.

Size of the focused spot of an EZP designed with 8mm focal length for 635nm illumination at 45° was profiled against micromirror rotation angle by measuring the far-field angular beam divergence (θ) of the Gaussian beam, and calculating the focused beam waist (w_f) using the formula –

$$\theta \approx \frac{2\lambda}{\pi w_f} \quad (5)$$

The measured focused spot size shows little degradation (Figure 5) for micromirror scanning angles up to 10° (optical) about both axes.

Figure 5: Map of diameter of the focused spot (in microns) created by an EZP with 8mm focal length for 635nm illumination at 45° nominal incidence as function of optical angular deflection of the micromirror.

IMAGING RESULTS

Transmission Barcode Imaging using EZP Micromirror

Preliminary testing of image-formation capabilities of the device was performed in a simple transmission-mode experiment, depicted in figure 6. A sample with spatially-varying transmission was placed in the focal plane of a scanning EZP, and transmitted light was concentrated into a photodetector using two collection lenses. Mylar transparencies printed with longhorn logos and numbers were imaged (Figure 7) using the system at 5 frames/second. Comparison with images obtained from an Olympus BX51 microscope using 10X objective indicated an estimated field of view of $1\text{mm} \times 0.35\text{mm}$ at approximately $15\mu\text{m}$ resolution.

EZP Micromirror-Based Reflectance Confocal Imaging

The devices were then incorporated into a portable bench-top single-fiber laser-scanning reflectance confocal microscope

Figure 6: Schematic of transmission-mode imaging experiment used for preliminary device testing.

Figure 7: Results of imaging Mylar transparencies using preliminary transmission-mode imaging experiment. (a-b) Image calibration: (a) Image of number 100 (transparent) in opaque background, and (b) Image of sample using Olympus BX51 confocal microscope. (c-d) Image of longhorn symbol and text "TEXAS": (c) using the device, and (d) using Olympus BX51 confocal microscope. Scale Bar: $250\mu\text{m}$.

Figure 8: Schematic of single-fiber laser-scanning reflectance confocal microscope incorporating the micromirror with monolithically integrated EZP.

(Figure 8) that is better suited to eventual use in *in vivo* imaging applications. Polarized light from a 635nm semiconductor laser

diode is launched into a single-mode polarization-maintaining fiber, aligned to the fiber slow axis. After collimation into a beam matched to the size of the EZP, the linearly polarized light is converted into circularly polarized light by a quarter-wave plate (QWP) before being simultaneously focused and scanned across the sample by our device. Reflected light from the sample maintains some component of circularly polarized light, which is converted into light linearly polarized along the fiber fast axis, orthogonal to the incident illumination. This allows the walk-off polarizer to separate the sample reflection from laser illumination and direct it to an avalanche photodetector. Images using this system of a USAF1951 resolution target obtained are depicted in figure 9.

Figure 9: Results of imaging USAF1951 resolution target using laser-scanning reflectance confocal experiment using the device. Images of groups of elements from different parts of the target are depicted in (a)-(b). Field of view is $1\text{mm} \times 0.35\text{mm}$, and resolution is $\sim 15\mu\text{m}$. (c) Image of the target using Olympus BX51 confocal microscope with corresponding locations marked by colored rectangles.

Field of view of $1\text{mm} \times 0.35\text{mm}$ and lateral resolution of $15\mu\text{m}$ are estimated based on calculating the line width of the resolvable features in the resolution target images.

CONCLUSIONS

Novel monolithic integration of reflective binary-phase-modulation elements on two-axis MEMS scanning micromirrors is

demonstrated for simultaneous beam scanning and focusing in a compact single-chip solution. This approach can potentially eliminate the need for focusing optics in a microendoscopes catheter, thus simplifying assembly and improving form factor. Elliptical zone plates integrated on two-axis self-aligned staggered vertical comb driven micromirrors, incorporated into a laser-scanning reflectance confocal microscope experiment, were shown to provide the cellular-level resolution required in microendoscopes without complex multi-element assembly.

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