FR4 Laser Scanner With Dynamic Focus

Serhan O. Isikman, *Student Member, IEEE*, Randy B. Sprague, and Hakan Urey, *Member, IEEE*

***Abstract*—An electromagnetically actuated optical scanner made using standard printed circuit board technology with integrated dynamic focusing feature is presented. Dynamic focus is achieved with an independently controlled plunger machined on the flame retardant-4 (FR4) platform. Integration of a laser diode and lens, torsional scanner, and the plunger for dynamic focus adjustment on FR4 platform greatly improves the form factor of the device for imaging applications. A peak-to-peak mechanical scan angle of 50° is achieved. The dynamic focus control allows for shifting the beam waist location from 80 mm up to 650 mm.**

***Index Terms*—Dynamic focus, extended depth of focus, integrated optics, magnetic actuators, optical scanner.**

I. Introduction

OPTICAL scanners are at the heart of many photonic applications. They allow steering a focused spot to address any point on a surface of interest within their field of view. This function is utilized in numerous applications including, but not limited to, 2-D imaging and display [1], optical coherence tomography [2], and laser scanning microscopy [3]. Scanning systems employ optics to achieve a focused spot on the screen. Therefore, conventional scan engines employing passive focusing optics suffer from limited depth of focus, determined by the Rayleigh range of the beam. Hence, a variable focus mechanism is highly desired in most scanning applications. Different solutions have been proposed in the literature to extend the depth of field of scanning systems. Flexible optics such as liquid lenses [4] and deformable mirrors [5] have been used to achieve focal length modulation of the collimation optics. Refractive index modulation for dynamic focusing has been realized with acousto-optic [6] and liquid crystal lenses [7]. Scanners with moving lenses have also been devised [8].

In this work, we present for the first time a variable focus laser light source integrated with a scanner using standard printed circuit board (PCB) technology, which is an ideal platform for integrating electrical, mechanical, and optical components [9]. Flame retardant-4 (FR4) is used as the main PCB substrate and has well-engineered mechanical properties that allow for moving large masses at large deflections and low powers.

Manuscript received September 11, 2008; revised October 21, 2008. First published December 09, 2008; current version published February 04, 2009. This work was supported by Microvision Inc. The work of H. Urey was supported by a TÜBA-GEBİP award.

S. O. Isikman was with Koç University, Rumelifeneri Yolu TR-34450 Sariyer, Istanbul, Turkey. He is now with the Integrated Nanosystems Research Facility, University of California, Irvine, CA 92697 USA.

R. B. Sprague is with Microvision Inc., Redmond, WA 98052 USA (e-mail: sid_madhavan@microvision.com).

H. Urey is with Koç University, Rumelifeneri Yolu TR-34450 Sariyer, Istanbul, Turkey (e-mail: hurey@ku.edu.tr).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2008.2010139

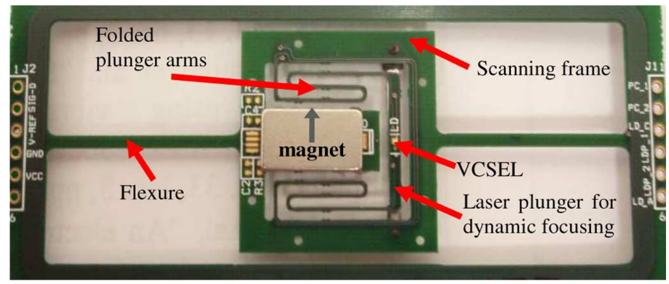

Fig. 1. Picture of the PCB-based torsional scanner suspended with two flexures integrated with a laser plunger element. Torsion magnet magnetization direction is indicated with an arrow. Although not show in the picture, the scanning board above is soldered to a 1.5-mm-thick PCB board (bridge board) using pin headers on the two sides, providing rigidity to the assembly, as well as carrying out the signals on the scanner board. The external coil for torsion is mounted on the bridge board.

The main contribution of this letter is the integration of a two degree-of-freedom (DOF) scanning system with a die laser and lens on a compact FR4 platform. FR4 offers readily available electrical interconnections, magnetic actuation, and sensing coils for easy integration.

II. Device Operation

A. Structure of the Scan Engine

The scanner presented in this work is shown in Fig. 1. It is produced from a 300-μm-thick PCB sheet made of FR4, which is essentially an epoxy fiber-glass composite material, with copper laminates on both sides [9]. The torsional scanning frame is suspended by two torsional flexures. The dynamic focusing element (called the *laser plunger* throughout the text) is essentially a folded cantilever structure carrying a laser diode at the tip and is cut inside the scanning frame. The folded flexures holding the paddle, which carries the vertical-cavity surface-emitting laser diode (VCSEL), are designed to make the laser plunger structure compliant to reduce the power requirements. The laser diode on the plunger is translated out-of-plane with respect to a fixed focusing lens that is placed on the scanning frame to achieve dynamic focusing.

B. Torsional Scan Operation

Torsional scanning is achieved by physically scanning the red VCSEL (from Vixar Inc.) placed on the plunger rather than bouncing the beam from a scanning mirror. This approach makes the dynamic focusing practical and results in a highly integrated photonic module. The torsional actuator is moving magnet type. A neodymium permanent magnet of dimensions $12 \times 7 \times 2$ mm is mounted on the scanning frame. The magnet is poled in-plane and normal to the flexures. A 3-mm-thick

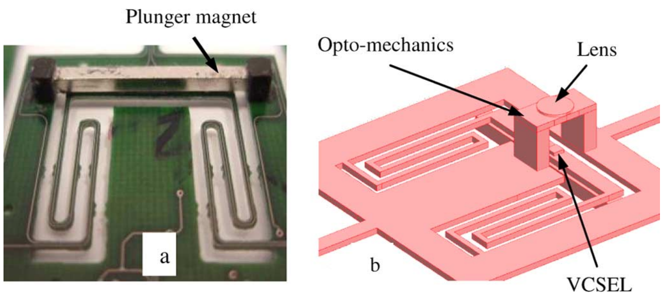

Fig. 2. (a) Close-up picture of the moving coil laser plunger actuated by an external magnet mounted on the torsional frame underneath the plunger paddle. The actuation coil is routed on the plunger arms. The magnet is elevated from the surface to leave enough clearance for plunger deflection (bottom view). (b) Illustration of the focusing optics assembly on the FR4 scanner used to focus the laser beam (top view).

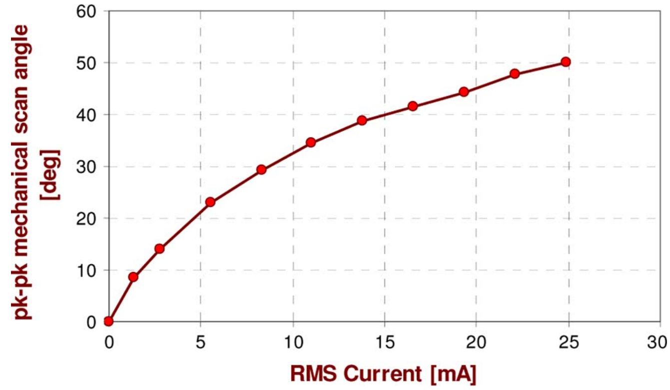

Fig. 3. Peak-to-peak angular mechanical deflection of the torsional scanner at resonance as a function of rms current through the torsional drive coil. Motor efficiency drops down with increasing scan angle, due to large deflections, resulting in the nonlinear behavior in the deflection curve.

external coil with a radius of 10 mm is mounted below the magnet with 5-mm gap, for resonating the scanner at 60 Hz. A 50° peak-to-peak mechanical scan angle is achieved at 80-mW root-mean-square (rms) power. Since the laser is scanned physically, the mechanical scan angle is equal to the optical scan angle.

C. Dynamic Focusing Operation

The main function of the integrated dynamic focusing feature on the torsional scanner is to allow pointing the laser beam to a point in the field of view of the scanner with a focused spot. Since a tight focused beam diverges quickly, a dynamic focusing feature becomes valuable for applications requiring small spot size in a range longer than the Rayleigh range of the beam.

A laser plunging element is cut inside the scanning frame to allow for out of plane deflections of the laser diode. A VCSEL is wire-bonded to the electrical connections on the paddle of the plunger, which is suspended by two folded arms to increase the compliance. The plunger arms connect to the scanning frame. Four copper lines are routed on the 0.5-mm-wide plunger arm, two of which are for electrical connection to the laser and two for the magnetic actuation coil of the plunger. An external permanent magnet is placed underneath the plunger paddle with sufficient clearance for deflections. The magnetic field of this magnet interacts with the current through the paddle to actuate the plunger out-of-plane with Lorentz forces. A 6-mm focal length lens with 2.8-mm diameter is mounted on the scanning frame with a plastic optomechanical holder. This optical unit moves with the torsional scanning frame. The alignment tolerance of the VCSEL with respect to the lens is less than 100 μm, which causes about 15 mm of pointing error in the worst case. Fig. 2 shows a picture of the moving coil laser plunger together with a drawing of the focusing optics assembly mounted on the torsional frame. As the plunger is actuated, its paddle moves out-of-plane modulating the distance between the laser diode and the fixed focusing lens, varying the output beam waist distance from the scanner. Small deflections of the plunger tip result in a long shift of the focused spot depth due to large longitudinal magnification of the system. To avoid mechanical coupling of the torsion mode to the plunger operation, out-of-plane deflection mode of the plunger is designed to be at 150 Hz and the actuation is off-resonant for controllability of the plunger. As the laser plunger moves out-of-plane, it also slightly rotates. For 250-μm deflection, the pointing error caused by this effect is less than 0.5 mm at a distance of 1 m. Furthermore, to avoid the tilting of the plunger in operation, its tilting mode is designed to be at a much higher frequency to make it much stiffer.

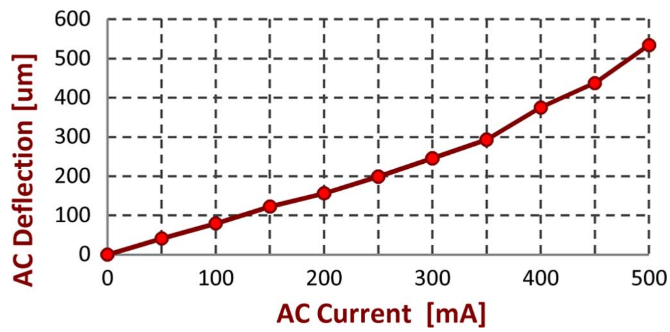

Fig. 4. Peak-to-peak out-of-plane deflection of laser diode plunger for off-resonant ac actuation at 25 Hz. The nonlinear behavior can be explained by the increased motor efficiency when plunger gets very close the external magnet at large deflections.

Different material properties for each mode of actuation are used for FR4 in finite-element modeling due to its anisotropic nature. For the torsion mode, the effective torsional modulus is $G = 6.5$ GPa and for the out-of-plane plunger mode, the effective Young's modulus is $E = 50$ GPa. For both modes, Poisson's ratio is 0.2.

III. Experimental Results

Fig. 3 shows the peak-to-peak mechanical deflection angle of the scanning frame as a function of the actuation coil current. As seen from the figure, the efficiency of torsional drive reduces at large deflection angles due to the change in the magnet-coil distance. The laser plunger can be concurrently actuated out-of-plane to modulate the beam waist distance. Fig. 4 shows the ac deflection of the laser plunger tip as a function of the drive current. At large deflections, the plunger gets very close to the external magnet, increasing the magnetic motor efficiency. Therefore, deflection is observed to be nonlinear with the drive current for large deflections.

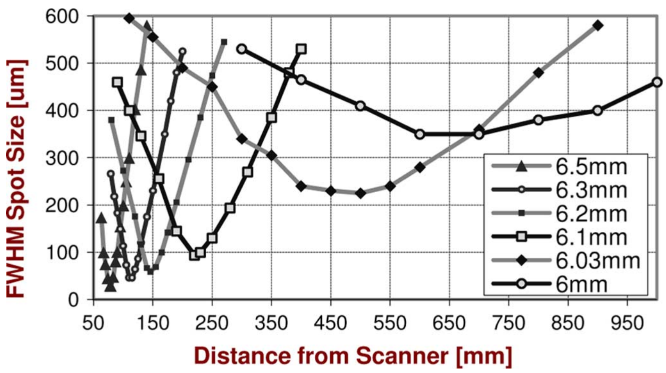

Fig. 5. Experimental results for the spot size as a function of distance from the scanner. Each curve represents the depth of focus of the beam for a varied laser-to-lens distance as shown in the legend. The total travel range of the VCSEL is about 500 μm.

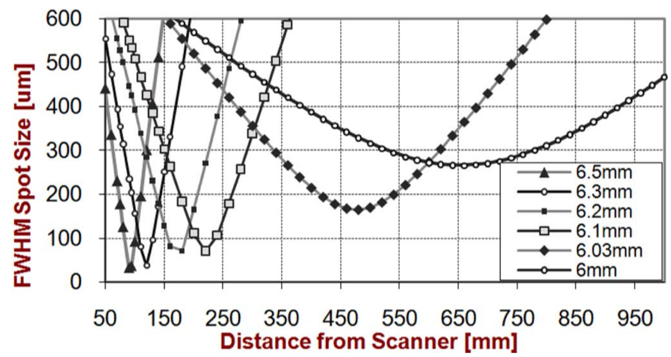

Fig. 6. Theoretical curves for the spot size as a function of distance from the scanner. Each curve represents the depth of focus of the beam for a varied laser-to-lens distance as shown in the legend.

The beam waist location is sensitive to tiny deflections of the plunger element due to large magnification. Therefore, accurate off-resonant controllability of this element is essential; thus it is actuated off-resonance.

The location of the beam waist can be calculated using the imaging equation for Gaussian beams [10]

$$\frac{1}{d_0 + z_R^2/(d_0 - f)} + \frac{1}{d_i} = \frac{1}{f} \quad (1)$$

where d_o denotes the laser diode distance to the lens, d_i denotes the beam waist (image) location, f is the focal length of the lens, and z_R is the Rayleigh range of the beam on the object side given by

$$z_R = \frac{\pi\omega_0^2}{\lambda} \quad (2)$$

where ω_0 is the $1/e^2$ beam waist radius on the object side and λ is the wavelength of the beam.

Fig. 5 shows the experimentally obtained depth of focus curves for the scanning beam. Each curve shows the full-width at half-maximum (FWHM) spot size as a function of the propagation distance for a different laser diode position with respect to the fixed lens on the scanning frame. The laser diode is displaced a total of 500 μm with the plunger actuation, shifting the beam waist location from 80 to 650 mm after the lens. As an example, if the FWHM spot size required for reading a 5-mil (125 μm) barcode is 125 μm, dynamic focus system allows for extending the depth of focus from about 60 to 250 mm. For applications requiring a spot size of 500 μm (20 mils), the depth of focus can be increased to one meter. The plunger can be deflected more to further extend the depth of field. Hence, the dynamic variable focus feature allows the torsional scanner to scan a long range from almost contact up to one meter with the flying spot always in focus.

Fig. 6 shows the theoretical depth-of-focus curves for the same cases as shown in Fig. 5. The DOF curves are calculated by using the imaging equation given in (2). The wavelength of the VCSEL is 672 nm and its numerical aperture is 0.1. An inspection of the calculated DOF curves reveals that the experimental and theoretical results are in good agreement.

IV. CONCLUSION

FR4 and standard PCB technology is used to integrate two DOF scanner and associated electromagnetic actuators with a VCSEL and focusing optics on the moving platform. A 50° scan angle is achieved with resonant magnetic actuation at 60 Hz and 500-μm peak-to-peak deflection is achieved with an off-resonant laser diode plunger on the same platform. The imaging range with 125-μm spot size is extended from 50 to 250 mm using a 6-mm focal length lens. FR4 is an ideal platform for moving few millimeter sized devices with large mass at low power consumption. FR4 scanners can offer significant advantages compared to microelectromechanical systems counterparts [11] in terms of integrability with optics and electronics, cost, fabrication time, and performance for low-frequency devices.

REFERENCES

[1] A. D. Yalcinkaya, H. Urey, and S. Holmstrom, "NiFe plated biaxial MEMS scanner for 2-D imaging," *IEEE Photon. Technol. Lett.*, vol. 19, no. 5, pp. 330–332, Mar. 1, 2007.

[2] A. Aguirre *et al.*, "Two-axis MEMS scanning catheter for ultrahigh resolution three-dimensional and En face imaging," *Opt. Express*, vol. 15, no. 5, pp. 2445–2453, 2007.

[3] H. Miyajima, K. Murakami, and M. Katashiro, "MEMS optical scanners for microscopes," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 3, pp. 514–527, May/Jun. 2004.

[4] S. Kuiper and B. H. W. Hendriks, *App. Phys. Lett.*, vol. 85, p. 1128, 2004.

[5] Y. Shao, D. L. Dickensheets, and P. Himmer, "3-D MOEMS mirror for laser beam pointing and focus control," *IEEE J. Sel. Topics Quantum Electron.*, vol. 10, no. 3, pp. 528–535, May/Jun. 2004.

[6] A. Kaplan, N. Friedman, and N. Davidson, "Acousto-optic lens with very fast focus scanning," *Opt. Lett.*, vol. 26, no. 14, pp. 1078–1080, 2001.

[7] M. Ye and S. Sato, "Liquid crystal lens with focus movable along and off axis," *Opt. Commun.*, vol. 225, no. 4–6, pp. 277–280, 2003.

[8] S. Kwon, V. Milanovic, and L. P. Lee, "Large-displacement vertical microlens scanner with low driving voltage," *IEEE Photon. Technol. Lett.*, vol. 14, no. 11, pp. 1572–1574, Nov. 2002.

[9] H. Urey, S. Holmstrom, and A. D. Yalcinkaya, "Electromagnetically actuated FR4 scanners," *IEEE Photon. Technol. Lett.*, vol. 20, no. 1, pp. 30–32, Jan. 1, 2008.

[10] S. A. Self, "Focusing of spherical Gaussian beams," *Appl. Opt.*, vol. 22, pp. 658–661, 1983.

[11] A. D. Yalcinkaya, H. Urey, D. Brown, T. Montague, and R. Sprague, "Two-axis electromagnetic microscanner for high resolution displays," *IEEE J. MEMS*, vol. 15, no. 4, pp. 786–794, Aug. 2006.