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Beam-clipping-induced diffraction effects in MEMS laser scanners for autostereoscopic outdoor displays☆

Jörg Reitterer[a,d,*], Franz Fidler[a], Gerhard Schmid[a,b], Christian Hambeck[c], Ferdinand Saint Julien-Wallsee[a], Walter Leeb[b], Ulrich Schmid[d]

[a] TriLite Technologies GmbH, Werner von Siemens Straße 1, 7434, Neutal, Austria
[b] Institute of Telecommunications, Vienna University of Technology, Gußhausstraße 25, 1040, Vienna, Austria
[c] Institute of Computer Technology, Vienna University of Technology, Gußhausstraße 27-29, 1040, Vienna, Austria
[d] Institute of Sensor and Actuator Systems, Vienna University of Technology, Floragasse 7, 1040, Vienna, Austria

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ABSTRACT

In micro-electro-mechanical systems (MEMS) laser scanners, the beams reflected by the micromachined mirror may be truncated at various edges in the system, e.g., due to finite size of the reflective mirror surface, at the rigid supporting mirror frame, and at the package of the light source. In this paper the joint effect of such individual beam clipping is described by introducing a so-called effective system aperture. Diffraction effects induced by this virtual aperture are analyzed by means of Fourier optics incorporating the Fraunhofer far field approximation. The beam clipping theory is then applied to a laser light module with integrated MEMS mirror for autostereoscopic outdoor displays. Employing an optimization of the MEMS mirror tilting angle with respect to the laser light source, the beam-clipping-induced diffraction effects are minimized.

1. Introduction

Laser scanners with integrated micromirrors have been a driving application for the micro-electro-mechanical systems (MEMS) technology since the first scanning silicon mirror was published over three decades ago [1]. MEMS laser scanners consist of a laser light source with one or more laser diodes emitting light of usually different wavelengths, collimation optics, and at least one one-dimensional (1D) or a single two-dimensional (2D) scanning MEMS mirror, which are capable of deflecting the collimated light beams in one or two spatial dimensions. These scanners are employed in a variety of different display applications, such as flying spot pico projectors [2], large-scale autostereoscopic outdoor displays [3–5], head-up displays [6], and retinal scanning displays [7]. Other applications range from confocal microscopy [8] and optical coherence tomography (OCT) [9] to light detection and ranging (LIDAR) [10], laser printers [11], bar code readers [12], and optical cross-connects [13].

Basically, MEMS laser scanners can be classified either by their operation principle (reflective micromirror, refractive microlens, and diffraction grating), their actuation principle (electrostatic, electromagnetic, piezoelectric, electrothermal, and magnetostrictive), or the fabrication technology (surface micromachining, bulk micromachining, and hybrid technologies) [2]. As most of the MEMS laser scanners make use of torsional reflective mirrors fabricated by silicon bulk micromachining with only the actuation principle varying [14], the analysis in this paper is limited to this approach. In the specific application of autostereoscopic, i.e., glasses-free, three-dimensional (3D) outdoor displays, electromagnetically actuated torsional MEMS mirrors with a reflective operation principle are employed.

For many applications the quality of the scanned laser beams is crucial, e.g., for autostereoscopic outdoor displays where the divergence angle of the collimated laser beams is the most important system parameter since this optical parameter is directly related to the maximum distance at which a viewer can perceive the stereoscopic effect [3–5]. The major optical limitations of MEMS laser scanners are the static and dynamic flatness of the scanning mirror as well as the clipping of the reflected beam, e.g., due to the finite size of the reflective surface. Dynamic mirror deformation is caused by large acceleration forces during the mirror movement. Even a low amount of bending of the reflective mirror surface can lead to detrimental wavefront distortions and hence, to increased

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* Corresponding author at: TriLite Technologies GmbH, Werner von Siemens Straße 1, 7434 Neutal, Austria. Tel.: +43 720 347290 30; fax: +43 720 347290 90.
E-mail address: reitterer@trilite-tech.com (J. Reitterer).

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divergence angles of the reflected beams in the far field. If the maximum mirror deformation is smaller than $\lambda_{min}/10$, where λ_{min} is the shortest wavelength of the laser scanner system, the introduced distortions can be neglected [7,15]. The dynamic deformation can be minimized by an optimized MEMS mirror design where the values of the mirror size and thickness, as well as maximum scanning angle and frequency are carefully selected [16]. If static and dynamic mirror deformations are negligible—which is assumed in this paper—the optical properties of the system may be limited only by beam-clipping-induced diffraction effects leading to increased beam divergence in the far field of the MEMS laser scanner.

The dominant sources of beam clipping in MEMS laser scanners are the finite size of the reflective micromirror surface itself (i.e., if the beam diameter is larger than the MEMS diameter), the rigid mirror frame and the package of the light source. In this paper the combined effects of these individual mechanisms are described by introducing a so-called effective system aperture. Diffraction effects induced by the effective system aperture are analyzed by means of Fourier optics incorporating the Fraunhofer far field approximation [17].

As an example, the beam clipping theory is then applied to a laser scanner for autostereoscopic outdoor displays [3–5]. Fig. 1 shows the basic principle of this display. Each display element—a so-called "trixel"—contains a laser scanner which consists of three laser diodes (one each for red, green, and blue), associated monitor photodiodes, a plano-convex cylindrical microlens [18], and an electromagnetically actuated 1D MEMS mirror. The microlens collimates the three laser beams only in the horizontal z'-direction, generating narrow vertical stripes in the far field. The 1D MEMS mirror with the rotation axis parallel to the x'-axis scans the collimated light beams in the z'-direction. The MEMS mirror is actuated quasi-statically with a triangular signal at a frequency of $f_M = 60$ Hz. By modulating the optical output powers of the laser diodes during scanning, different image information can be sent to different tightly constrained directions in a time-multiplexed manner. This not only generates a stereo parallax (i.e., a viewer can see a different image with each eye) but also a movement parallax (i.e., a viewer can see different images when moving his head). The first-generation prototype display from [3] has a pitch between adjacent trixels of 12 mm. For comparison, state-of-the-art two-dimensional (2D) LED displays for outdoor applications nowadays have pixel pitches of up to 30 mm. The total number of pixels ranges from a few pixels for small signs to millions of pixels for large-scale billboards. By employing the mathematical framework for analyzing beam-clipping-induced diffraction effects in MEMS laser scanners, the trixel system design is optimized for an existing MEMS mirror model. By solving a nonlinear optimization problem, an optimal tilting angle of the MEMS mirror with respect to the laser light source is derived, where the different clipping mechanisms are balanced in order to minimize the increase in divergence angles at the extrema of the scanning position.

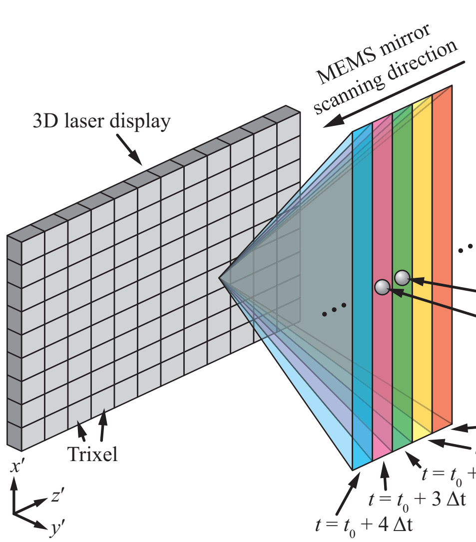

Fig. 1. Basic principle of the time-multiplexed autostereoscopic multi-view laser display with Δt as the time interval between the subsequent illumination of adjacent 3D viewing zones.

2. Fourier-optical description of beam-clipping-induced diffraction

2.1. Beam clipping mechanisms and effective system aperture

The geometry of a general MEMS laser scanner is shown in Fig. 2(a). In this paper, for the sake of simplicity both, the whole MEMS mirror as well as the reflective surface, are tilted only with respect to the x-axis. An extension of the beam clipping theory taking an additional rotation axis into account, e.g., for 2D MEMS mirrors, is rather straightforward.

In the simplest embodiment, the package of the light source contains a single laser diode, as well as collimation optics in the form of a single microlens. Without loss of generality, the beam clipping formalism presented in this paper can be readily applied to more complex light sources, e.g., light sources with multiple laser diodes and beam combiners with a system of microlenses. The collimation optics can be described by their two principal planes P_1 and P_2. For many applications a minimization of the collimated beam's divergence angle is desired, which can be achieved by placing the front facet of the laser diode at a distance of $d_1 = f$ to the first principal plane P_1, where f is the focal length of the optical system. The collimated beam propagates a distance of d_2 from the second principal plane P_2 to the exit aperture of the light source package, which in this case is assumed to be sufficiently large in order to avoid any beam clipping. The distance between the light source package exit aperture and the center of the MEMS mirror's reflective surface is denoted d_L. The reflective surface of the MEMS mirror is assumed to be either elliptical or rectangular with $d_{M,x}$ and $d_{M,y}$ as the ellipse's major and minor axes (or vice versa) or as the rectangle's side lengths, respectively. The MEMS mirror frame is modeled as a rectangle with $d_{F,x}$ and $d_{F,y}$ as the corresponding side lengths.

The MEMS mirror frame is tilted with respect to the light source package by an angle α. The mechanical tilting angle of the reflective surface with respect to the frame is denoted β. Since the laser beam is deflected by an angle of $\varphi = \pi - 2(\alpha + \beta)$, the deflected beam is described in the coordinate system (x, y, z), which is rotated with respect to the source coordinate system (x', y', z') by φ.

The three relevant causes for beam clipping are indicated by red dots in Fig. 2. "M_1" and "M_2" represent clipping by the finite reflective surface. The degree of truncation depends not only on the diameter of the reflective surface $d_{M,x}$ but also on beam's angle of incidence $\alpha + \beta$ with respect to the surface normal. Especially for small values of $d_{M,x}$—as shown in Fig. 2(b)—the clipping at the finite reflective surface can be significant. For tilting angles $\beta > 0$, there might be an additional beam clipping at the MEMS mirror frame represented by "F" (cf. Fig. 2(a)). For deflection angles of $\varphi > \pi/2$, the beam is deflected back to the light source and—depending on the values of φ and d_L—might be clipped by the light source package, indicated by dot "L" in Fig. 2(c). For sufficiently large values of d_L, this clipping mechanism can be completely prevented. However, an important design goal for most applications is to minimize the overall size of the MEMS laser scanner module, which imposes an application-specific upper limit on d_L.

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