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Laser Beam Characterization using Agile Digital-Analog Photonics

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ABSTRACT

Precise knowledge of laser beam parameters is a key requirement in many photonics applications including for lasers and optics used in the transportation industry. This paper reports on a novel motion-free laser beam characterization system using electronically agile digital and analog photonics such as a Digital Micromirror Device (DMD) and an analog variable focal length lens. The proposed system has the capability of measuring all the parameters of a laser beam including minimum waist size, minimum waist location, beam divergence and the beam propagation parameter (M^2). Experimental results demonstrate the measurement of the minimum beam waist size and location for a test 633 nm fundamental mode Gaussian laser beam. The system is also applicable for imaging of arbitrary beams including non-laser beams.

Keywords: Beam parameters, Gaussian beams, Digital Micromirror Device, Beam Profiler and Imager

1. INTRODUCTION

Laser beams are highly monochromatic in nature and unlike infinite plane waves, are of finite extent in the transverse direction and spread with the propagation distance. The most widely encountered type of laser beam has a Gaussian intensity distribution at planes normal to the propagation direction. A Gaussian laser beam is completely characterized for all distances from the source by only two parameters, i.e., the minimum beam waist radius and the location of the minimum waist [1]. Precise knowledge of these values is critical for many applications including but not limited to laser manufacturing, machining, optical communications, laser-based imaging, optical materials research, optical metrology, radar, and laser damage studies. Prior art methods [2-7] to measure these parameters require either the motion of optical elements in the beam path or the motion of the entire beam profiler/imager assembly over large distances, leading to a beam analyzer that is slow, cumbersome, and inherently suffers from poor measurement repeatability. In this paper, a new motion-free beam analyzer instrument is presented and experimentally demonstrated that engages an analog-mode Electronically Controlled Variable Focus Lens (ECVFL) in conjunction with a Digital Micromirror Device (DMD)-based beam profiler [8-12] to accurately measure the parameters of a Gaussian laser beam that overcomes prior art limitations [13]. Future work for this analyzer is also highlighted indicating the power of this beam analyzer.

2. PROPOSED LASER BEAM ANALYZER SYSTEM

Fig. 1 shows the proposed laser beam characterization system. The laser beam under test passes through the ECVFL placed a fixed distance d_2 from the DMD-based beam profiler/imager. The key idea is that instead of profiling/imaging the laser beam at multiple locations along the beam path, the beam is profiled at the fixed DMD-plane for multiple values of the ECVFL focal length f using the DMD-based beam profiler operating in knife-edge profiling mode [8, 10-11]. The measured $1/e^2$ beam radius w(f), in terms of test laser beam unknown parameters of minimum beam waist w_0 and minimum beam waist location a distance d_1 in front of the ECVFL are derived using the ABCD matrix propagation law [1] and is given by [13]:

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$$w^2(f) = w_0{}^2\left[\left(1 - d_2/f\right)^2 + \left\{\frac{\lambda\left(d_1 + d_2 - d_1 d_2/f\right)}{\pi w_0{}^2}\right\}^2\right], \qquad (1)$$

where λ is the wavelength of the laser. By varying f and measuring the corresponding value of w(f), a set of simultaneous equations in w_0 and d_1 are found. The least-squares solution of these simultaneous equations gives the values of w_0 and d_1.

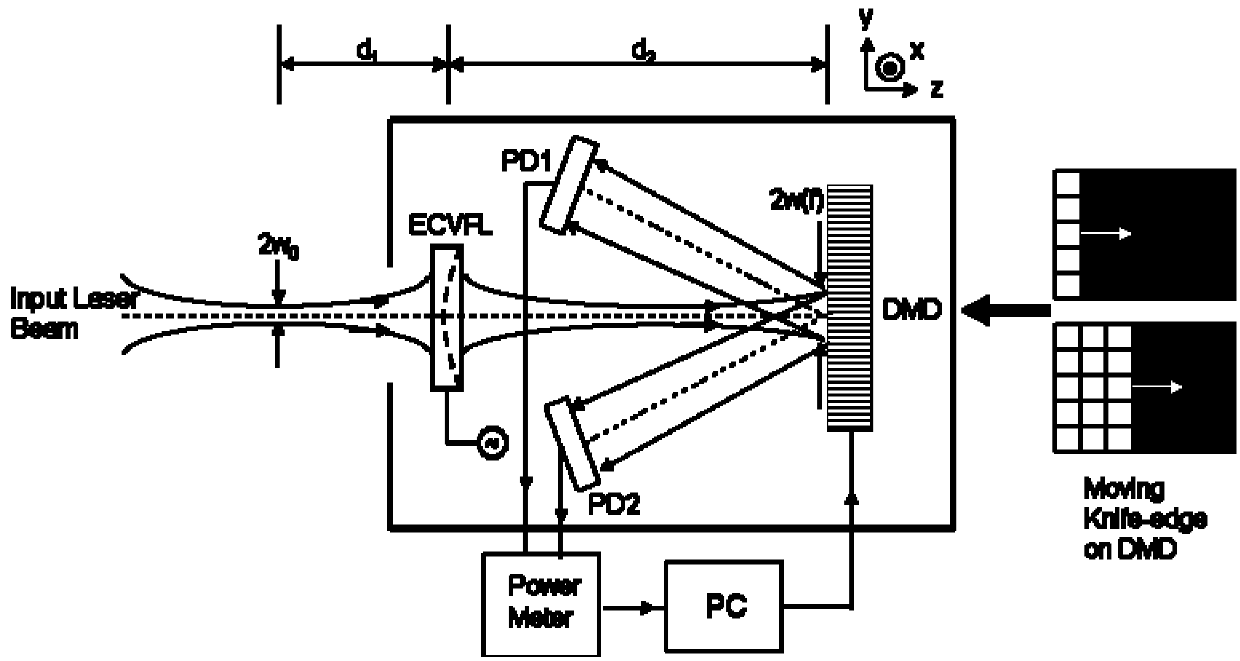

Fig. 1. Proposed motion-free laser beam characterization system using an Electronically Controlled Variable Focus Lens (ECVFL) and a DMD-based optical beam profiler/imager. PD1/PD2: Photo-detectors; PC: Personal Computer.

3. EXPERIMENTAL RESULTS

The Fig. 1 system is set up in the laboratory. A 10-mW λ = 633 nm MellesGriot He-Ne Model 05-LHP-991 laser is used as the test source. The ECVFL used is a Varioptic Arctic 320 liquid lens that changes focus based on the Electrowetting principle [14]. The DMD is placed a fixed distance d_2 = 30.8 cm from the ECVFL. Figs. 2 shows the measured $1/e^2$ beam radii in the horizontal (fig.2(a)) and the vertical (Fig.2(b)) directions for different values of the ECVFL focal length f along with the respective least-square curve fits from Eq. (1). According to the curve fit, the values of the unknown parameters are found to be w_{0H} = 324.27 μm, d_{1H} = 25.8 cm, w_{0V} = 324.71 μm and d_{1V} = 25.1 cm. Using these values, the beam divergence half-apex angle is found to be 0.62 mrad in both directions [1]. These values are in excellent agreement with the laser manufacturer datasheet values of minimum beam radius w_0 = 325 μm and beam divergence half-apex angle θ = 0.62 mrad.

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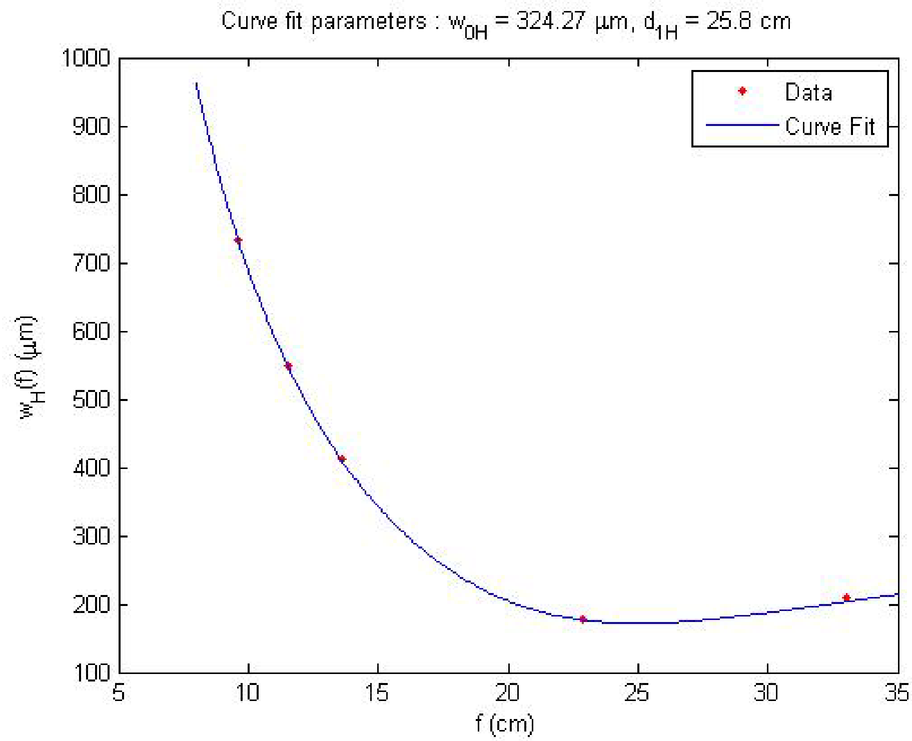
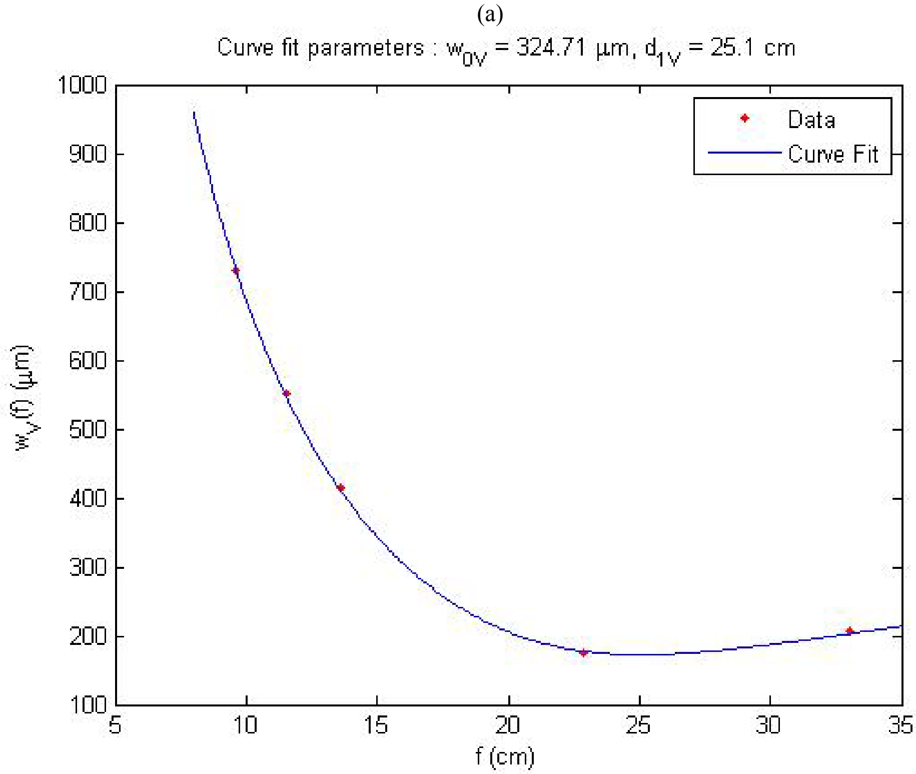


(a)



(b)

Fig. 2. Eq.1 least squares curve fit for determining test laser beam parameters in (a) Horizontal direction and (b) Vertical direction.

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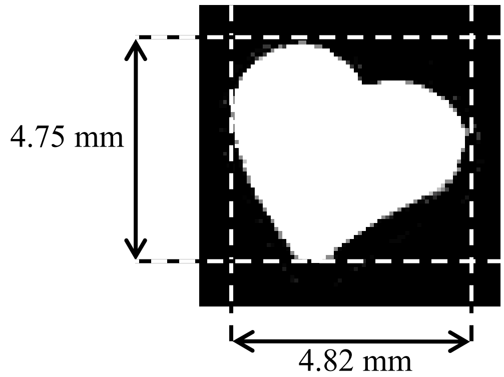
4. IMAGING OF ARBITRARY BEAMS



(a)

(b)

Fig.3(a) IR heart object image captured by an IR CCD; (b) Heart image formed using the DMD-based profiler/imager system.

The Fig.1 DMD-ECVFL system is fundamentally a Three Dimensional (3-D) optical imager of incident arbitrary (and non-laser source) optical beams. Specifically, the DMD scans the optical irradiance falling on the DMD plane (or image sampling plane) using x-y micromirror/pinhole motion while the ECVFL adjusts the projected 3-D light irradiance image plane slice on the DMD plane [15]. Depending on the irradiance source (e.g., laser beam or 3-D object scattered incoherent light illumination) providing the light imaged on to the DMD plane, appropriate collection lens optics can be added to the $+\theta$ and $-\theta$ deflection light paths off the DMD to collect the pin-hole scanned light. As PD1 and PD2 gathered light power corresponds to the total light in a given instantaneous light irradiance image on the DMD plane, one can always normalize the PD1 and PD2 light power readings per DMD/ECVFL scan setting. Hence, any temporal variations of the incident irradiance image during the pinhole and focus scanning processes can be accounted for during the full image reconstruction signal processing using the independent PD1 and PD2 readings. Hence, a temporally robust optical imager of time varying light beams is formed. Fig.3 shows some initial imaging results of a heart shaped optically luminous object that has been reconstructed using the pin-hole sampling operation of the Fig.1 basic imager system with Fig.3(a) showing the heart object image captured by an IR CCD and Fig.3(b) showing the heart image formed using the DMD-based system.

In the context of lasers, the Fig.1 system can be used to measure the all-important beam propagation parameter M^2 for multimode Gaussian beams [13] by using the DMD-based beam profiler in pinhole-profiling mode [12]. The proposed system can further be extended to measure the M^2 parameter for any

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arbitrary monochromatic optical beam as the ABCD matrix formalism for beam propagation through an optical system holds for any general optical beam using the second-moment definition of the laser beam width [16]. Furthermore, the system can also be extended to chromatic beams using the beam width and chromatic beam factor M_{λ}^2 definitions given in Ref.17 [17]. In this case, the ECVFL and the DMD used would need to be dispersion-free over the optical wavelengths spread and instead of using point photo-detectors PD1 and PD2, the DMD-based beam imager would need to use two spectrometers as wavelength sensitive detectors. A variety of spectrometer designs can be used in the Fig.1 system; hence the Fig.1 system is also a hyper-spectral imager capable of imaging chromatic images/beams.

5. CONCLUSION

It has been shown for the first time how a motion-free laser beam propagation analyzer system using an ECVFL and a DMD-based optical beam profiler can be used to completely characterize a fundamental mode Gaussian laser beam. Furthermore, the system can also be used to analyze multimode Gaussian beams and any arbitrary monochromatic optical beam including chromatic beams. Future work will demonstrate these extensions of the basic ECVFL-DMD-based optical imager, including applications to broadband imaging.

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