Continuous Laser Generation of Ultrasound

James N. Caron[1,2,a)] and Gregory P. DiComo[1]

[1]*Research Support Instruments, 4325-B Forbes Boulevard, Lanham, MD 20706, USA*
[2]*Quarktet, 205 Indian Spring Drive, Silver Spring, MD 20901, USA*

[a)]Corresponding author: Caron@RSImd.com

Abstract. Pulsed lasers have been used to generate ultrasound in materials for the purposes of nondestructive evaluation. The deposited energy heats the localized area rapidly, producing an ultrasonic wave by thermoelastic expansion. Detection of the ultrasound provides information about the material, such as thickness, strength, and the presence of defects.

Alternatively, a continuous-wave laser can be scanned across the sample surface using a fast steering mirror or rotating polygon mirror. As the optical beam moves across the surface, the deposited energy creates thermoelastic expansion along the scanning line. With sufficient energy and scanning speed, a ultrasonic wavefront is generated.

Continuous Laser Generation of Ultrasound has the potential to scan an object several orders of magnitude faster than pulsed laser generation. To create detectable ultrasound with frequencies near 1 MHz, pulsed lasers with over 100 mJ per pulse and pulse widths of a few nanoseconds are required. Commercially available lasers with sufficient power and pulse width are limited to repetition rates between 10 and 400 Hz. A meter-long B-scan with millimeter resolution would at best take 2.5 seconds without signal averaging. A squared meter C-scan with millimeter resolution would take between 42 minutes and 28 hours. By contrast, a CLGU system could scan a single line in less than a millisecond and perform the full C-Scan in less than a second.

INTRODUCTION

Ultrasonic sensing is a conventional method of nondestructive evaluation to evaluate material strength and locate defects. Pulsed lasers have been studied as a means to generate the ultrasound in the material without direct contact. [1, 2, 3] Deposited energy from a pulsed laser heats the localized area rapidly, inducing thermoelastic expansion in the material and giving rise to an ultrasonic wave. Detection of the ultrasound provides information about the material, such as thickness, strength, and the presence of defects.

For Continuous Generation of Ultrasound (CLGU) [4], a high-power continuous-wave (cw) laser can be used to continuously generate ultrasound in the material. [5] The cw laser beam is scanned across the sample surface by reflection from a fast steering mirror or a rotating polygon mirror as depicted in Figure 1. As the optical beam scans across the surface, deposited energy creates ultrasound by thermoelastic expansion along the scanning line. The superposition of waveforms creates an ultrasonic wavefront to propagate. Any disruptions in the sensed wavefront can be directly associated with material defects.

To create detectable ultrasound with frequencies around 1 MHz, pulsed lasers with energies that exceed 100 mJ per pulse and have pulse widths of a few nanoseconds are used. Commercially available lasers with these capabilities are limited to repetition rates between 10 and 400 Hz. To achieve millimeter resolution, a meter-long B-scan would require between 2.5 and 100 seconds. A squared meter C-scan with millimeter resolution would take at best 42 minutes with a 400 Hz repetition rate. In contrast, a CLGU system with equal spot size and sufficient power could perform the B-line scan in less than a millisecond and perform the squared meter C-Scan in under a second.

CONCEPT

CLGU scanning time estimates are calculated by comparing the energy deposited by a pulsed laser with that of the scanning cw laser, assuming equivalent wavelength and spot size. The deposited energy of a pulsed laser with total

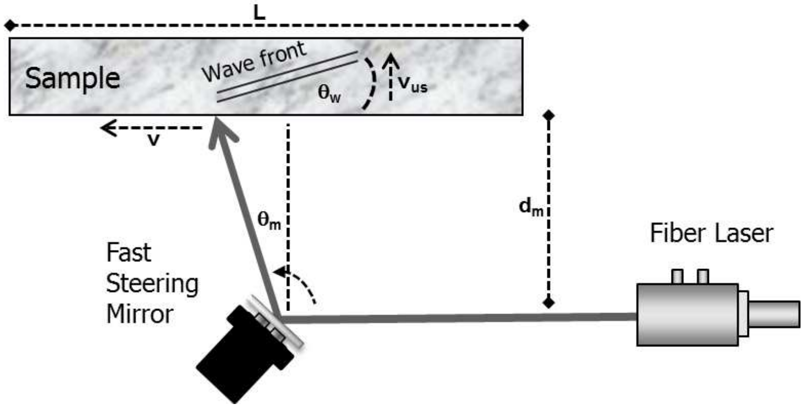

FIGURE 1. A fast steering mirror directs the cw laser beam across the material surface. The deposited energy creates an ultrasonic wavefront as a result of the rapid heating. The superposition of ultrasound waves along the scan line produces an ultrasonic wavefront that propagates into the material.

power P_p, spot radius of a, and temporal width of w at point (x_o, y_o) on the surface can be represented as

$$E(x_o, y_o) = \int_{-\infty}^{\infty} AP_p e^{\frac{-2t^2}{w^2}} dt = \sqrt{\frac{\pi}{2}} wAP_p \tag{1}$$

where A is the fraction of the light absorbed by the material.

The deposited energy for a scanning laser of power P_s and scanning rate v_s at the same point is

$$E(x_o, y_o) = \int_{-\infty}^{\infty} AP_s e^{\frac{-2(v_s t)^2}{a^2}} dt = \sqrt{\frac{\pi}{2}} \frac{a}{v_s} AP_s. \tag{2}$$

By equating the energy deposited by the scanning beam to the energy deposited by the pulsed beam, the required scanning speed is

$$v_s = \frac{aP_s}{wP_p}. \tag{3}$$

Values from empirical research can be used to establish the scanning speeds. From previous research [5], a pulsed laser will produce a detectable ultrasound wave in a graphite-reinforced composite panel with w =5 ns, a =2.5 mm, and P_p =4.2 MW. Assuming the cw laser power is P_s =10 kW, the scanning velocity required to create the equivalent ultrasound is v_s =1.2 km s^{-1}. As such, a one meter B-scan can be performed in 0.84 milliseconds. A one meter-squared C-scan with millimeter resolution can be finished in 0.84 seconds provided the detection and data acquisition systems can keep the same rate.

The scanning rate is dependent on the beam size. If we consider a cw laser with equal irradiance but a different beam radius b, the power distribution is expressed as

$$P(x, y, t) = \frac{P_b b^2}{a^2} e^{\frac{-2((x - x_o - v_s t)^2 + (y - y_o)^2)}{b^2}} \tag{4}$$

where $P_b b^2 a^{-2}$ is the total power of the laser. The deposited energy is then

$$E(x_o, y_o) = \sqrt{\frac{\pi}{2}} \frac{b^2}{a v_s} P_b \tag{5}$$

producing a scanning rate of

$$v_s = \frac{b^2 P_b}{a w P_p}. \tag{6}$$

Thus, a larger beam size requires a faster scanning rate. The scanning rate for a beam radius of $b = 4$ mm and power of 10 kW is 3.05 km s^{-1}.

The conversion from light energy into thermal energy takes places on a picosecond timescale, [6] several orders of magnitude faster than the pulse width of the laser light. Thus, the frequency distribution of the pulsed-laser generated ultrasound is strongly dependent on the temporal shape of the laser pulse. For CLGU, the scanning rate and spot size will determine the frequency distribution of the ultrasound wave. A faster scan rate will produce a faster temperature rise, increasing the frequency of the ultrasound. An estimate of the frequency can be derived from the scanning rate and beam radius,

$$\nu \approx \frac{v_s}{2a}. \tag{7}$$

Thus a scanning rate of 1.2 km s^{-1} and beam radius of 2.5 mm would produce a central frequency around 0.24 MHz. A scanning rate of 3.05 km s^{-1} and beam radius of 4.0 mm produces a wavefront with frequency of 0.76 MHz. Since the primary frequency can be controlled using spot size, a frequency of 1.52 MHz can be achieved by reducing the spot radius to 2.0 mm.

TECHNOLOGY

This technique depends on three main components: a cw laser of sufficient power, an extremely fast scanning mechanism, and a method to detect the wavefront.

Fiber lasers are a natural choice for CLGU, offering high average power. Since their inception in the 1990s, the output power of Ytterbium-doped fiber lasers has increased exponentially [7] with commercial units achieving 50 kW [8]. The improvements in power have been driven largely by developments in pumping technology and improved handling of nonlinear damage mechanisms in the gain fibers. Primarily used for cutting sheet metal, these lasers are commonplace in industrial settings.

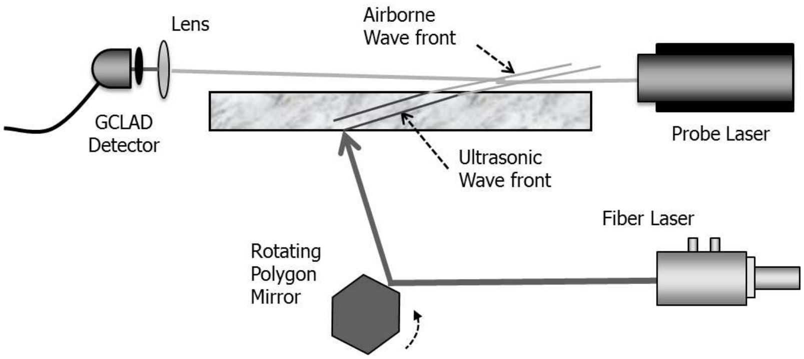

FIGURE 2. Ultrasonic wavefronts are created in a material using CLGU. A portion of the wave radiates into the air and continually deflects a probe laser beam. A defect in the material will disrupt the wavefront causing a corresponding change in the GCLAD signal.

The important characteristics of the scanning device are frequency $\nu_m = v_s/L$, and angular range $\theta_m = \arctan(L/2d_m)$ where L is the length of the scan and d_m is the normal distance from the sample to the mirror, as shown in Fig. 1. With these parameters, d_m can be determined using $d_m = v_s/(2\nu_m \tan\theta_m)$.

To reach these scanning speeds, rotating multi-facet polygonal mirrors may have the best potential. This technology is relatively simple, well established and can achieve the required scanning speeds and ranges, while handling the high laser power. For example, a high performance gas bearing scanner using a 35-facet rotating polygon mirror was demonstrated to achieve 81,000 rpm. This translates to scanning frequency of 2.3 kHz with 10 degrees of range, producing $d_m = 1.8$ meters. [9] Additional optics can be added to ensure that the spot size remains constant on the material surface. [10]

Detection can be accomplished using a transducer array, a scanning interferometer, or a static GCLAD sensor [11] as depicted in the figure. For initial tests, an array of contact transducers on the reverse side of the sample can be used to verify the generation of a wavefront. [12, 13] For noncontact detection, a probe laser beam could be scanned in sync with the scanned generating beam. The scattered light would be collected into an interferometric system to detect the wavefront. [1, 14] If the material moves transversely to the scanning line, as would happen on an assembly line, Gas-coupled Laser Acoustic Detection (GCLAD) would be an attractive option. [11] In this method, a cw laser beam is sent parallel to the surface of the material. Ultrasound waveforms in the material are radiated into air at the material/air interface, as shown in Fig. 2. The airborne waves pass through the probe beam causing the deflection and displacement of the laser beam and sensed by a position-sensitive photodetector.

Possible applications include inspecting advanced materials during and after production, perform 2D inspections of products on rapidly moving production lines such as foils and composites, inspecting large scale structures, such as combat vehicles, drones, and ship panels, and using a portable system to scan tunnels and rail lines.

REFERENCES

[1] M. Choquet, C. Padioleau, R. Hon, P. Houchard, C. Néron, and J.P. Monchalin, "Laser Ultrasonic Inspection of the Composite Structure of an Aircraft in a Maintenance Hangar," in *Review of Progress in Quantitative Nondestructive Evaluation 14*, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York, pp. 545-552 (1994).

[2] C.B. Scruby and L.E. Drain, *Laser Ultrasonics*, Adam Hilger, Bristol, (1990).

[3] J.P. Monchalin, "Laser-ultrasonics: from the laboratory to industry," in *Review of Progress in Quantitative Nondestructive Evaluation 23A*, edited by D. O. Thompson and D. E. Chimenti, AIP Conference Proceedings, vol. 700, American Institute of Physics, Melville, NY, pp. 3-31 (2004).

[4] J.N. Caron, "Continuous Laser Generation of Ultrasound," U.S. Patent Application # 20110048135, March 3, 2011.

[5] J.N. Caron, G. P. DiComo, and S. Nikitin, "Continuous laser generation of ultrasound for nondestructive evaluation." in *Review Of Progress In Quantitative Nondestructive Evaluation*, AIP Publishing, **31** Vol. 1430(1), pp. 243-250 (2012).

[6] J.B. Spicer, *Laser Ultrasonics in Finite Structures: Comprehensive Modelling with Supporting Experiment*, Ph.D. Thesis, Johns Hopkins University, (1991).

[7] D.J. Richardson, J. Nilsson, and W.A. Clarkson, "High power fiber lasers: current status and future perspectives [Invited]," *J. Opt. Soc. Am. B*, **27**(11), B63B92 (2010).

[8] IPG Photonics, 50 Old Webster Road, Oxford, MA 01540 USA.

[9] M. Sweeney, E. Erdelyi, M. Ketabchi, and B. Kent, "Design Considerations for Optical Pointing and Scanning Mechanisms," in *Proceedings of SPIE, 5176*, Optomechanics, pp. 135-146, (2003).

[10] L. Beiser, "Design equations for a polygon laser scanner," In *Beam Deflection and Scanning Technologies*, International Society for Optics and Photonics, pp. 60-66, (1991).

[11] J.N Caron, Y. Yang, J.B. Mehl and K.V. Steiner, "Gas-coupled Laser Acoustic Detection at Ultrasonic and Audible Frequencies,"*Review of Scientific Instruments*, **69**(8), pp. 2909-2911 (1998).

[12] X. C. Jin, F. L. Degertekin, S. Calmes, X. J. Zhang, I. Ladabaum, and B. T. Khuri-Yakub, "Micromachined Capacitive Transducer Arrays for Medical Ultrasound Imaging," in *Proc. Ultrason. Symp.*, pp. 1877-1880 (1998).

[13] A. Jain, D. Greve, and I. Oppenheim, "A MEMS Phased Array Transducer for Ultrasonic Flaw Detection," in *IEEE Sensors*, pp. 515-520 (2002).

[14] H. Voillaume, D. Simonet, C. Brousset, P. Barbeau, J-L. Arnaud, M. Dubois, T. Drake, M. Osterkamp,"Analysis of Commercial Aeronautics Applications of Laser Ultrasonics for Composite Manufacturing," *Proceedings of ECNDT 2006*, 9th European Conference on NDT, Berlin, Germany, pp. 1-8 (2006).