



Lock-in Thermography using High-Power Laser Sources

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Abstract

Optical lock-in thermography is a completely contactless and very sensitive NDT technique. As an optical source of energy, incandescent lamps are most commonly used because they are relatively inexpensive and offer high irradiances at the test specimen. However, they are strongly restricted by their low modulation bandwidth with a maximum modulation frequency of only about 1 Hz. The use of high-power kilowatt-class laser sources, e.g. diode laser arrays, pushes this constraint beyond 100 Hz. This allows for the exploration of the near-surface region of metals and layer systems with better and more accurate penetration depth and depth resolution. Moreover, these lasers are virtually free of any additional thermal radiation that could interfere with the “true” thermal response emitted from the heated sample. In turn, they can be easily used in a one-sided test configuration. We present current activities with kilowatt-class high-power laser sources for advanced lock-in thermography and focus on the application of laser arrays that offer a very high irradiation strength over a large sample area beyond the mentioned advantages.

1. Introduction

Optically excited thermography is, besides being completely contactless, a very sensitive NDT technique. As an optical source of energy, incandescent (i.e., halogen) lamps or flash lamps are most commonly used because they are relatively inexpensive and offer high irradiances at the test site. Flash lamps allow a pulse-shaped surface heating while with halogen lamps a temporally modulated surface heating can be realized. These two temporal regimes have become established as pulse thermography (a.k.a. flash thermography) and lock-in thermography. Both regimes offer specific advantages and disadvantages regarding the detection sensitivity and test duration (1). Lock-in thermography can be used to achieve a very high detection sensitivity, especially for deep lying defects, since a correlation is made over a long measuring period with a sufficiently phase-stable measuring chain consisting of a function generator, light source and thermographic camera. On the other hand, pulse thermography often provides a comparable detection sensitivity for the detection of near-surface defects within a few seconds, if a light source with a sufficiently high irradiance is present, e. g. flash lamps on the order of 100 Wcm^{-2} (2). Now, the question arises whether it is possible to use lock-in thermography for both tasks – deep and shallow defects. Since halogen lamps have a very low modulation bandwidth (cw to a few Hz), their probing depth is limited to comparatively thick layers, depending on the material being investigated (3). To remove these and other limitations, the use of high-power lasers is a very promising option.

2. Laser Thermography – Evolution from a highly specialised into a versatile tool for NDT

Laser thermography has its roots in the late-1960s when Kubiak (4) first used a focused light source to raster-scan a specimen containing surface breaking cracks and employed an infrared detector to monitor the blocking effect of the cracks on the heat flow. Nowadays, this technique has evolved into the flying-spot laser thermography (5-8). In the mid-1970s, when Rosencwaig and Gersho worked out the theory for the photoacoustic effect (9), they laid the foundation for the development of the photothermal testing methodology. The decisive difference to the flying-spot technique is that in the photothermal methodology, a high-frequency modulated laser beam is used, which explicitly uses the concept of the thermal wave (3, 10). Starting in the 1980s, infrared cameras came into play and enabled full-field thermal imaging (11), but this time, slow thermal light sources were used. Today, flash lamps (pulsed planar heating) and halogen lamps (modulated planar heating) have been established as the standard light sources for the specific regimes of pulsed and lock-in thermography. Only recently, the availability of novel technologies – fast and high-resolution infrared cameras, innovative brilliant laser sources and high-performance data acquisition and processing technology – has enabled a paradigm shift from the separated photothermal and thermographic methodologies to a versatile tool for NDT that combines both approaches. In addition, the heating can also be spatially structured using laser arrays (12). This new degree of freedom allows the development of completely new thermography NDT methods (13-15).

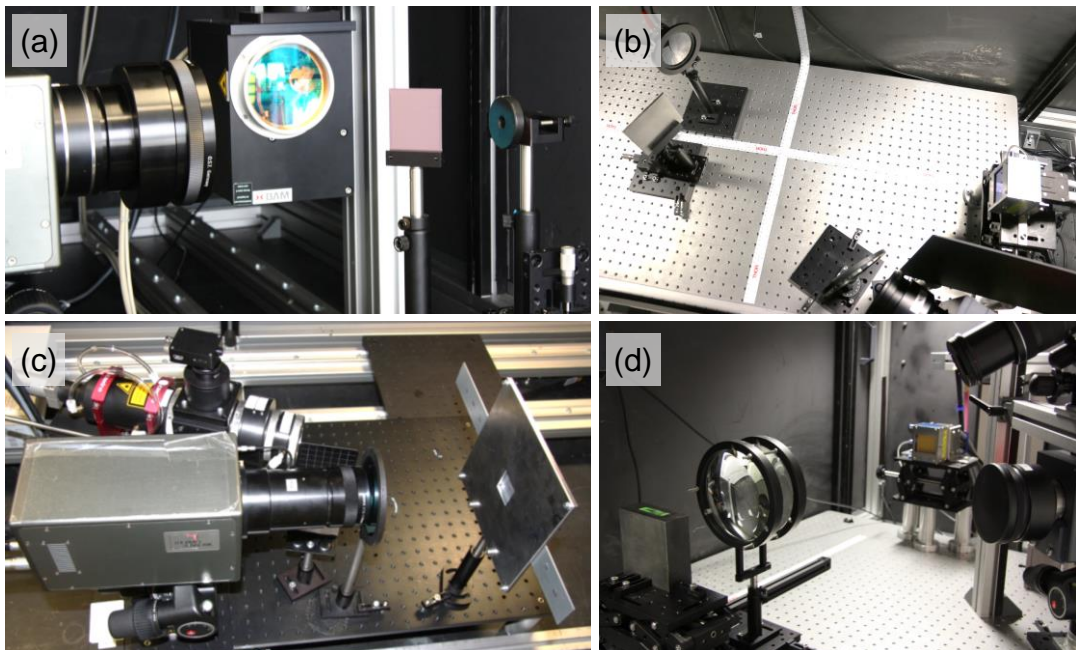


Figure 1. Typical laser thermography setups used at BAM: (a) Flying-spot laser thermography using a fibre-coupled diode laser coupled to a 2D scanner, (b) Lock-in thermography using a VCSEL laser array, (c) Pulsed thermography using a fibre-coupled diode laser coupled to a square-shaped beam homogenizer, (d) Laser projected photothermal thermography using VCSEL laser array with individually controllable emitter lines projected via a lens system onto the sample.

3. The wavelength advantage

Various methods of laser thermography are implemented at BAM, such as flying spot, pulsed thermography, lock-in thermography, laser-projected photothermal thermography and are available for several inspection tasks such as the detection of cracks on or below the surface, the detection of voids or delaminations and layer thickness measurements. In Figure 1, some of the corresponding experimental setups are displayed. The first big advantage of lasers over other optical energy sources is the fact that they feature a predominantly monochromatic emission spectrum. If diode lasers are used, this emission is based on electroluminescence. As such they are virtually free of any additional thermal radiation that could interfere with the “true” thermal response emitted from the heated sample, see Figure 2. And, their emission spectrum is even more narrow than that of LEDs. In turn, they can be easily used in a single-sided test configuration, as for instance for testing resistance spot welds (16, 17) as shown in Figure 1 (c). In contrast, the classical optical energy sources such as halogen lamps or flash lamps are based on thermal emission and as such they always obey Planck's law of radiation. As a consequence, in addition to the main emission, they always emit a relevant portion of radiation in the infrared spectral range which overlaps with the spectral sensitivity range of the thermographic camera.

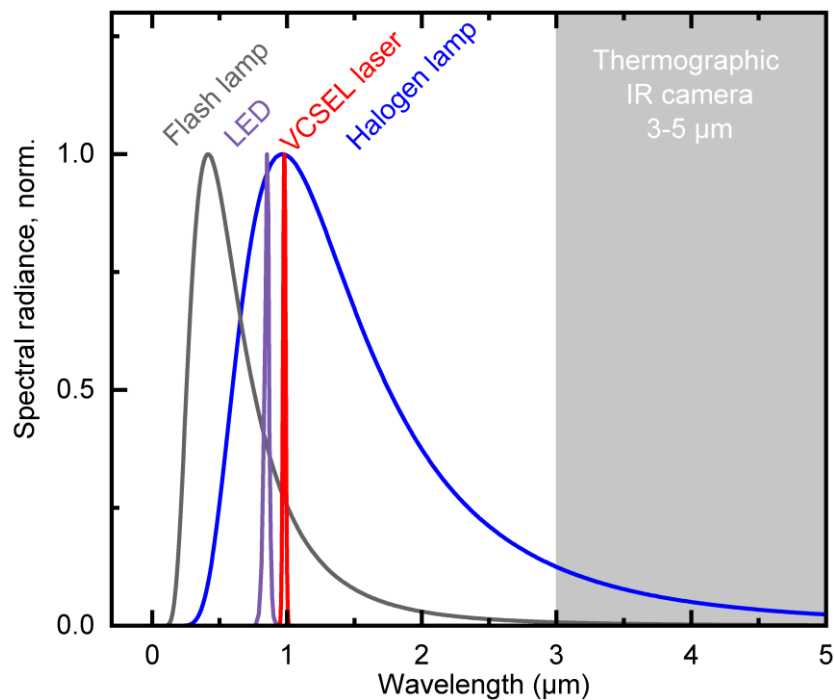


Figure 2. Emission spectra of typical optical energy sources compared to the spectral sensitivity range of a thermographic IR camera. The spectral radiance distribution of the flash lamp is approximated by that of a black body of 7000 K and that of a halogen lamp by that of a black body of 3000 K. The spectral radiance distribution of the high-power LED-array at BAM is centered around 850 nm and that of the high-power VCSEL laser array is centered around 980 nm.

4. The modulation frequency advantage

When high-power kilowatt-class laser sources, e.g. diode laser arrays, are used as thermal energy source, the mentioned constraint of the maximal modulation frequency can be pushed beyond 100 Hz, see Figure 3. This is two to three orders of magnitude faster than ordinary halogen lamps controlled by an electronic dimmer. Therefore, the use of such laser sources allows for the exploration of the near-surface region of metals and layer systems with better and more accurate penetration depth and depth resolution.

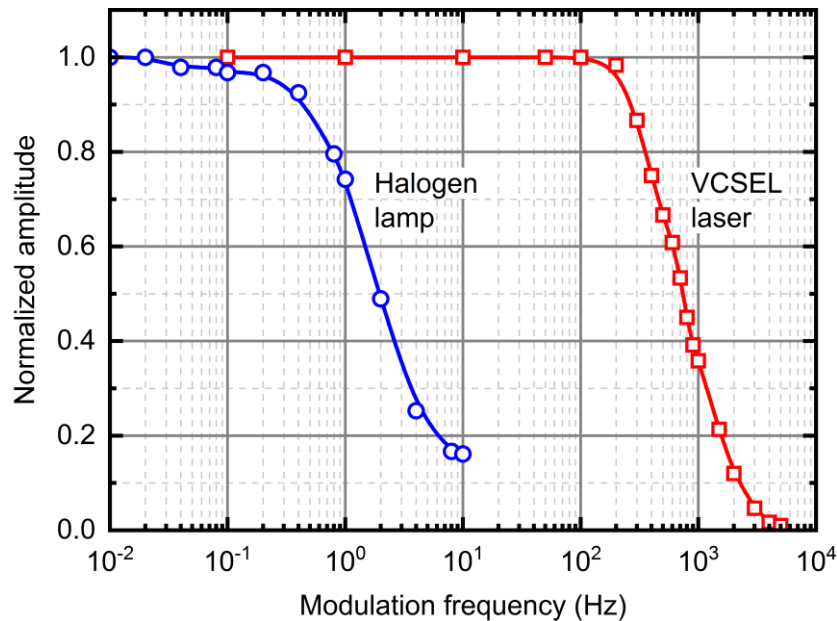


Figure 3. Normalized amplitude of the optical output power for a sinusoidal driving voltage depending on the modulation frequency for a high-power 2.4 kW VCSEL laser array (red squares) and for a 1 kW halogen lamp controlled by an electronic dimmer (blue circles).

5. The irradiance advantage

In a more general perspective, the significance of the laser for thermographic NDT can be summarized in Figure 4. This figure is calculated by using the 1D solution to the thermal heat diffusion equation together with the absorptance of the material which is illuminated with a harmonically modulated light source. This modulated heating provokes a temperature oscillation at the surface of the solid. As a second step, the corresponding oscillation of the total thermal emission is calculated using Stefan-Boltzmann law as a first order approximation and considering the emissivity of the materials. Within this framework the minimal irradiance of a light source necessary to provoke a measurable signal within a thermographic camera at a noise equivalent temperature difference (NETD) of 30 mK can be calculated. In Figure 4 this relationship is displayed for a wide spectrum of modulation frequencies and for several different light sources scaled to the same electrical input power (6 kW) and illumination area (100 cm²). Using this figure, it is now easily possible to analyze the range of materials to be tested using lock-in thermography, since only the materials (dotted lines) below the irradiance-vs-frequency curves (solid lines) are heated in excess of the

camera's NETD. Note that the displayed relations also scale with the square root of the number of correlated individual measurements. Essentially, this figure clearly shows that laser sources considerably increase the application range of lock-in thermography, since especially for metals with a high reflectance and high thermal diffusivity a high irradiance is vitally important to allow for lock-in thermography testing.

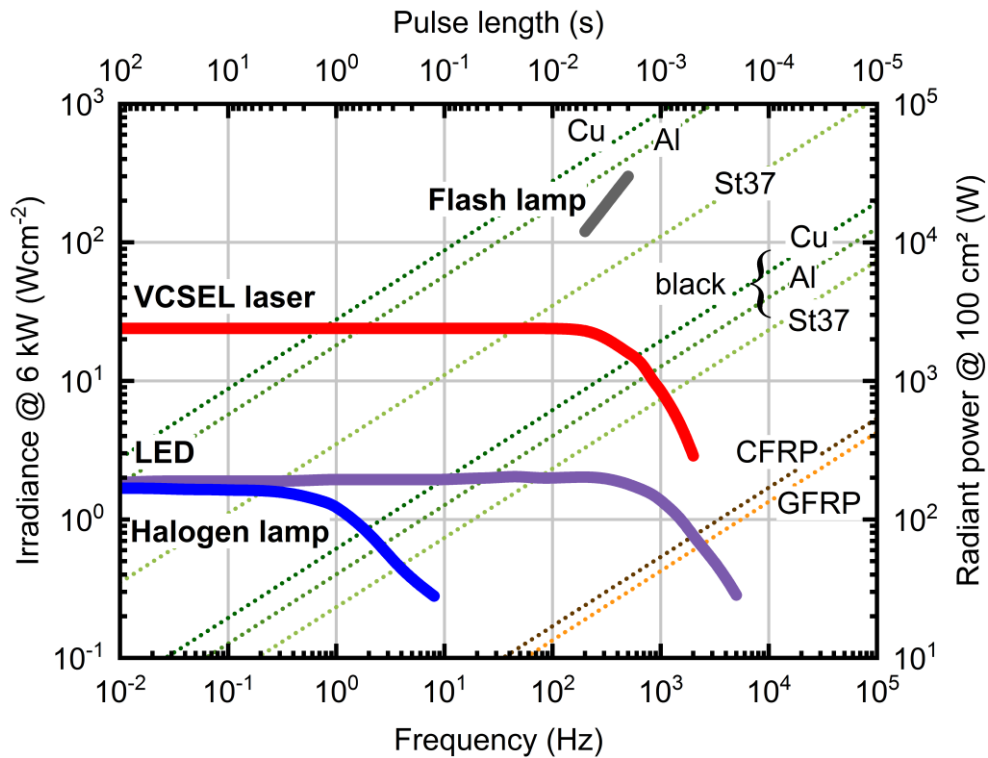


Figure 4. Theoretical minimal irradiance (dotted lines) of a light source vs. modulation frequency which is necessary to provoke a measurable signal within a thermographic camera (NETD of 30 mK). The colored dotted lines represent different materials as indicated. For the metals (greenish lines) another group is displayed where the surface has been blackened to an absorptance and emissivity of 0.95. The corresponding radiant power for an illuminated area of 100 cm^2 is given on the right axis. The colored thick solid lines indicate the irradiance-vs-frequency curves of three cw light sources (VCSEL laser array, LED array, halogen lamp), scaled to an electrical input power of 6 kW each together with a flash lamp at an electrical input energy of 6 kJ. All light sources illuminate a sample surface of at least 100 cm^2 .

Furthermore, it becomes clear that there is also a serious limitation for the use of the "workhorse" of thermographic NDT, the flash lamp in the area of highly reflective and highly thermally conductive metals such as copper and aluminium. This is a situation that is often encountered in thermographic testing practice. Only a surface treatment with black paint (c.f. the greenish group of lines in Fig. 4) makes these materials testable. On the other hand, only a limited frequency range is also currently available for the VCSEL laser arrays we use. But, by further power scaling or focusing, there is a high probability of eliminating this limitation in the future.

6. Conclusions

Thermographic NDT using the lock-in effect together with high performance thermographic cameras and high-power lasers as energy sources is a completely contactless and very sensitive NDT technique. Since thermal imaging cameras have penetrated the kHz range with high pixel counts, it has become obvious that only the use of suitable energy sources is needed to develop lock-in thermography into an even more versatile and accurate test method. The optical sources of choice are laser diode arrays, because they offer a lot of power on the test surface at high speed and at the same time flexibility.

References

1. Maierhofer C, Rollig M, Krankenhagen R, & Myrach P (2016) Comparison of quantitative defect characterization using pulse-phase and lock-in thermography. *Applied Optics* 55(34):D76-D86.
2. Krankenhagen R & Maierhofer C (2014) Measurement of the radiative energy output of flash lamps by means of thermal thin probes. *Infrared Physics & Technology* 67:363-370.
3. Almond DP & Patel PM (1996) *Photothermal Science and Techniques* (Chapman & Hall, London) p 241.
4. Kubiak EJ (1968) Infrared Detection of Fatigue Cracks and Other Near-Surface Defects. *Applied Optics* 7(9):1743-1747.
5. Li T, Almond DP, & Rees DAS (2011) Crack imaging by scanning laser-line thermography and laser-spot thermography. *Measurement Science and Technology* 22(3).
6. Schlichting J, Ziegler M, Maierhofer C, & Kreutzbruck M (2012) Flying laser spot thermography for the fast detection of surface breaking cracks. *18th World Conference on Nondestructive Testing, Durban*.
7. Ziegler M, Myrach P, & Neding B (2015) Wärmebehandlung und zerstörungsfreie Prüfung: Oberflächenrisse mit der Laser-Thermografie finden. *HTM Journal of Heat Treatment and Materials* 70(4):190-195.
8. Legrandjacques L, Krapez JC, Lepoutre F, & Balageas DL (1998) Detection of open cracks by a photothermal camera. *Review of Progress in Quantitative Nondestructive Evaluation, Vols 17a and 17b*:1959-1964.
9. Rosencwaig A & Gersho A (1976) Theory of the photoacoustic effect with solids. *J. Appl. Phys.* 47(1):64-69.
10. Mandelis A (2001) *Diffusion-Wave Fields: mathematical methods and Green functions* (Springer-Verlag).
11. Busse G, Wu D, & Karpen W (1992) Thermal Wave Imaging with Phase Sensitive Modulated Thermography. *J. Appl. Phys.* 71(8):3962-3965.
12. Ziegler M, Thiel E, & Studemund T (2018) Thermography using a 1D laser array – From planar to structured heating. *Materials Testing* in print.
13. Thiel E, Kreutzbruck M, & Ziegler M (2016) Laser-projected photothermal thermography using thermal wave field interference for subsurface defect characterization. *Applied Physics Letters* 109(12):123504.

14. Thiel E & Ziegler M (2017) Subsurface Defect Localization by Structured Heating Using Laser Projected Photothermal Thermography. *J Vis Exp* (123):e55733.
15. Thiel E, Ziegler M, & Studemund T (2018) Localization of subsurface defects in uncoated aluminum with structured heating using high-power VCSEL laser arrays. *Int J Thermophys* submitted.
16. Jonietz F, Myrach P, Suwala H, & Ziegler M (2015) Examination of Spot Welded Joints with Active Thermography. *Journal of Nondestructive Evaluation* 35(1):1.
17. Myrach P, Jonietz F, Meinel D, Suwala H, & Ziegler M (2017) Calibration of thermographic spot weld testing with X-ray computed tomography. *Quantitative Infrared Thermography Journal* 14(1):122-131.