10.21611/qirt.2016.104

Optical excitation thermography with VCSEL-array source

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Abstract

A novel VCSEL array combines the high temporal flexibility of a laser source with the full field radiation characteristics of an array and yields a new optical excitation source for active thermography that can merge the two regimes of flash and lock-in thermography. Among others, we investigate the possibility of multiplex photothermics for two-dimensional material characterization, e. g. thickness mapping. Several first test results will be presented that demonstrate possibilities and capabilities of this new optical excitation source and compare it to conventional sources.

1. Introduction

Optical excitation thermography (OTT) is a well-established non-contact and full-field imaging non-destructive testing method. It is generally used for damage detection as well as quality control and characterization for many different materials. It is highly automatable and provides objective results in a single-sided testing set-up. Optical excitation thermography is state of the art and is meanwhile widely used industrially by for example BMW and Airbus.

While there are several modern approaches in signal form and evaluation [1, 2], the two main regimes commonly known for achieving instationary heat diffusion necessary for active thermography use energy sources that can be controlled in either pulse mode (e.g. flash thermography) [3] or periodically. The former uses flash lamps with high power flash durations of less than 5 ms. The latter is also known as lock-in thermography [4] and employs lower power halogen lamps. Lasers can also be found in the field of OTT, although they are typically used in a different way. While the most common use of laser thermography is the so called flying spot method for quantitative crack detection and characterization, there are also applications with localized heat excitation [5].

2. State of the Art

2.1. Optically excited thermography

Lock-in thermography evolved as a multiplex variant of photothermics [6, 7], which is still used for material characterization, especially when it comes to investigate (thermally) thin layers or thermal material characteristics. The temperature-time data is pixel-wise Fourier-transformed in order to condense all available information into a phase and an amplitude image. Phase images are usually advantageous due to their insensitivity to inhomogeneous lighting and emission coefficients. Their depth range is usually twice as high as the amplitude images' depth range. The depth ranged is controlled via the thermal diffusion length $\mu = \sqrt{\alpha/_{\pi f}}$ that is dependent on the thermal diffusivity of the material and the Fourier-frequency. Typical frequencies are between 1 mHz and 1 Hz for plastics and between 0.1 Hz and 10 Hz for metals. Because the phase angle is related to the distance travelled of the thermal wave it can be used for quantitative evaluation of thicknesses [8]. There are, of course other methods and evaluation algorithms that provide similar results [9]. For investigating very thin layers, very high frequencies are necessary that cannot be provided by standard halogen lamps. For this, typically small spot or slightly widened lasers are used due to their high temporal dynamic. Measurements of areas become very time consuming due to the scanning test set-up. In addition thermal imaging system need to be able to record at least four images per lock-in period for correct evaluation of phase and amplitude; a considerable hardware requirement.

Fourier-transform is also applicable to flash thermography in a variant known as pulse-phase thermography (PPT, [3]). Due to the high power (several J) and short excitation time flash thermography provides a method that not only can probe a material with a broad spectrum but can also, after certain calibration, provide a quantitative determination of defect depth or material characteristics. However, for highly reflecting or high diffusive materials the amplitude provided for each spectral component decreases drastically and the signal-to-noise ratio quickly drops beneath the camera sensitivity. This is especially the case for low frequency components of the excitation pulse.

Vertical cavity surface emitting lasers (VCSEL) [10] are investigated as a possible solution for not only making full-field photothermal measurements possible, but also combining flash and lock-in excitation into one single device.

2.2. VCSEL as a thermography excitation source

VCSEL have been known for their rather low power, but have recently been improved towards a flexible, modular array with very high radiation powers [10, 11]. Simplification in production and large scale integration coupled with significant lower prices than comparable laser sources open up new applications in industrial heating processes. The device used at IKT emits infrared radiation at 980 nm and has a maximum power of 1.6 kW distributed over eight separate channels, each of which consisting of several thousand laser elements. It is shown in Fig. 1. The VCSEL driver unit is currently not yet synchronized with the infrared camera and the lock-in control software resulting in an unknown phase shift. This will be addressed in the near future.

Fig. 1. *VCSEL array at IKT*

Due to the lasers' divergence the array offers homogenous radiation in near and far field. This allows for applications with both small and very large specimens (e.g. fiber plastic composite aircraft structures). The device also has an advantage over visible light sources regarding thermal excitation of metal components, because the absorption coefficient of metals (e.g. aluminium) is significantly higher in the near infrared than in the visible spectrum. Thus, coupled with the very high output power, investigations of blank metal surfaces are possible without surface preparation. Due to a laser's high temporal dynamic the VCSEL device can bridge the gap between halogen lock-in-thermography and flash excitation through temporal pulse forming techniques. These have already been investigated theoretically and experimentally [1, 2], but the limited capability of conventional heat sources made this endeavour difficult.

Another advantage of laser source is the spectrally separated wavelength compared to the infrared imaging system which is in contrast to typical halogen lamp set-ups. Typically, curved specimens are difficult to test due to infrared reflections from the heat source into the camera. This can only be somewhat mitigated through filters and long-wave detectors.

3. Results of optical thermography testing with a VCSEL laser source

In this chapter we show first results produced with the VCSEL array excitation. All measurements are performed in lock-in mode skipping the comparison with flash thermography for now. Unless otherwise noted all images in this article are phase images with the lock-in frequency chosen for best defect contrast. Both, halogen lamps (up to 4.5 kW electrical power) and VCSEL array (up to 1.6 kW optical power), have been adjusted to heat the specimens' surfaces to approximately 35°C, in order to have comparable energy input into the specimens. All other parameters, e. g. measurement time or lock-in frequency, stayed the same when switching excitation source.

3.3. Comparison of VCSEL and halogen source for conventional applications

In order to substitute both conventional lock-in and flash thermography devices, the new light source must first be able to perform at least as good as its predecessors during conventional testing applications. A typical academic specimen used to evaluate thermography testing quality is a specimen with several flat-bottomed holes of different diameters and depths; the material in this case is CFRP (further details in [12]). As can be seen in Fig. 2 results from halogen lamp and VCSEL excitation, respectively, appear very similar. A closer look at the phase angle profiles in Fig. 2 (right) confirms the even quality of phase contrast. The phase shift is the result of the inherent phase shift of halogen lamps and the aforementioned lack of electronical synchronisation of the VCSEL driver unit.

Flat-bottomed hole specimen are of the most convenient specimens for active thermography. Their obvious rear surface structure allows for very academic validation of NDT methods. More realistic, yet still academic, are artificial impact damages in CFRP CAI (compression after impact) specimens. Due to their high occurrence and relevance one of

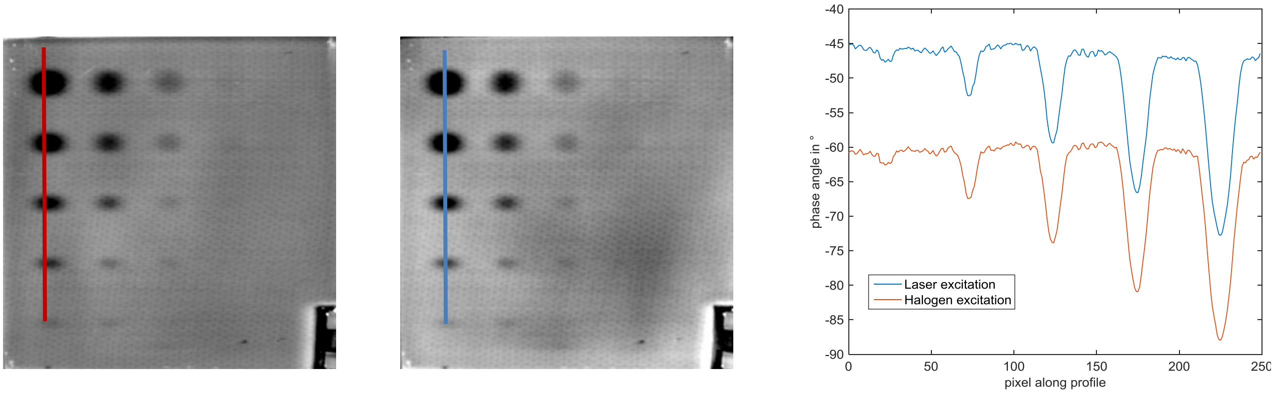

Fig. 2. *FBH specimen tested at 0.095 Hz lock-in-frequency with Halogen lamps (left) and VCSEL (right). Comparison of phase profiles on the right.*

these was tested and evaluated, too. Equivalent to the results of the FBH specimen the CFRP impact specimen was tested and evaluated. Accordingly, Fig. 3 shows that the phase contrast is highly reproducible between laser and halogen excitation.

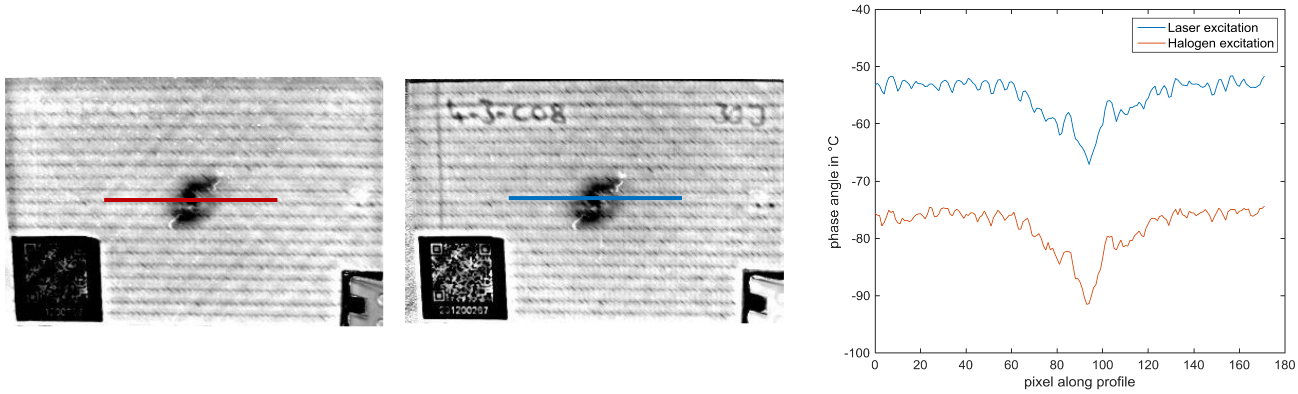

Fig. 3. *CFRP Impact specimen tested at 0.25 Hz lock-in-frequency with lamps (left and VCSEL (center). Comparison of phase profiles on the right.*

One of the advantages of laser excited thermography is the spectral separation of source and signal. The VCSEL array emits in the near infrared spectrum, while the IR-camera records heat radiation between 3 and 5 µm or 8 to 10 µm. A typical major problem of lock-in thermography is the continuous radiation of the hot lamps that may result in significant artifacts in the recorded data in case of curved specimen surfaces, whereof the thermal radiation is reflected and superposed on the specimen’s surface temperature. Similar problems may occur in flash thermography when hot flash lamps afterglow. Fig. 4 (left) shows an example of a thermography specimen with a curved surface, a CFRP landing flap. Fig. 4 (center) is a typical lock-in thermography result with halogen lamp excitation. One can clearly see the two bright reflections that impede proper testing. In contrast, the result in Fig. 4 (right) exhibits no artifacts due to reflected radiation and can therefore be evaluated more accurately.

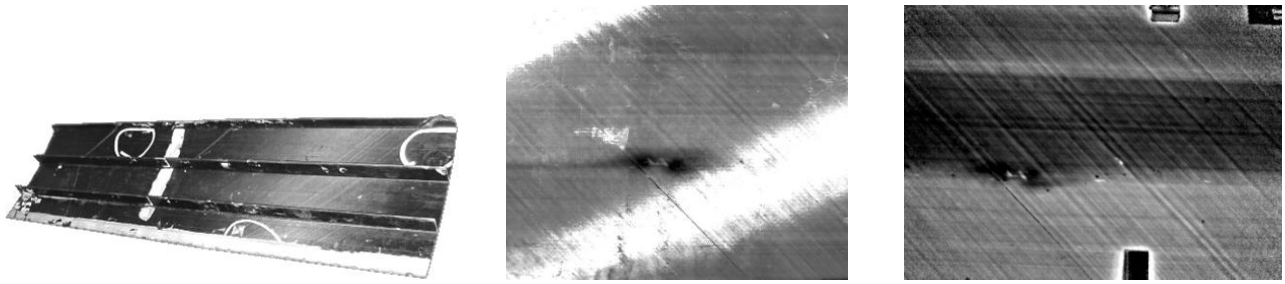

Fig. 4. *Curved CFRP landing flap. Photograph (left), Halogen lamp (center) and VCSEL (right) excited lock-in thermography results.*

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Similar results are demonstrated for an even larger CFRP specimen from the automotive sector. This 1.4 x 1.0 m² double-curved area can be fully tested in one shot as long as the geometric resolution achievable from the thermal imaging system satisfies the requirements. The lamps' reflections are clearly seen in Fig. 5 (left) and prevent reliable evaluation of possible defects. This specimen has several small impact damages that are marked in Fig. 5 (right). The bright spot just above the indicated impact damage is a marker glued to the rear side.

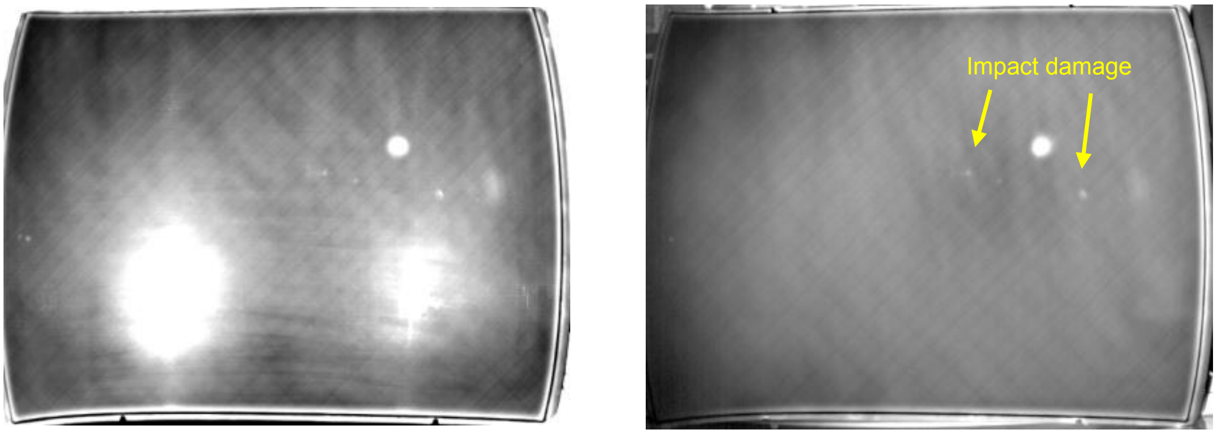

Fig. 5. *Halogen lamp (left) and VCSEL (right) excited lock-in thermography results for the large CFRP part*

As mentioned, metal parts suffer from very low absorption and emission coefficients in the visible spectrum. This leads to a twofold problem. First, heating the specimen to a substantial level with conventional sources is extremely difficult. Second, reflection of IR radiation as seen in the examples above may occur at curved surfaces. Such is the case for the titanium turbine blade in Fig. 6 (left). The comparison of the test results with halogen lamp excitation (Fig. 6 center) and VCSEL excitation (Fig. 6 right) demonstrates the viability of laser heating for metal specimens. The halogen lamps where driven at maximum power, while the laser was using only 25%, with both sitting at a distance of 1.2 m from the specimen.

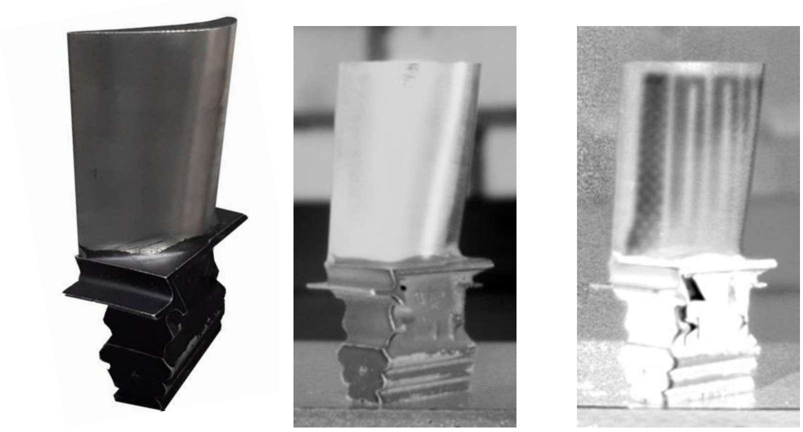

Fig. 6. *Titanium turbine blade: Photograph (left), Halogen lamp excited lock-in thermography result (center) and VCSEL excited lock-in thermography result (right)*

3.4. Temporal dynamic of laser excitation

Lasers and laser diodes are principally fast in their response time. They're mostly limited by the electronic driver unit. For photo thermal measurements or lock-in thermography with high frequencies (10…1000 Hz), respectively, a clean sine wave thermal signal is necessary, in order to quantitatively correlate phase angle measurements with thickness values. The theory therefor has been provided by [13]. The VCSEL unit has so far been characterized up to 50 Hz sinus modulation. As can be seen in Fig. 7 (left), output current rise and decay times well below 1 ms are available. Fig. 7 (right) shows that sine modulation signals of at least 50 Hz are easily achieved, with a theoretical possibility of several 100 Hz.

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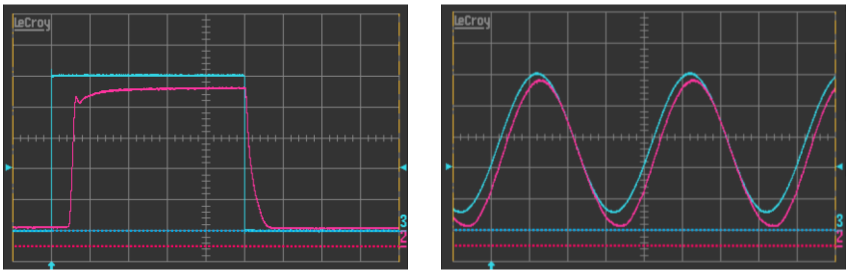

Fig. 7. *Left: Delay of output current pulse with maximum control input overdrive. Output current (magenta) and analog control signal (cyan). Timebase 2 ms/div. Right: 50 Hz sine modulation. Output current (magenta and analog control signal (cyan). Timebase 5 ms/div*

Preliminary results were made for the quantification of the thickness of ceramic coating (yttrium carbide) specimens on a stainless steel substrate. With lock-in frequencies up to 200 Hz (904 Hz camera frame rate) sine wave thermal signals on the specimens' surfaces were evaluated (see, for example, Fig. 8 (left) for a 20 Hz thermal signal). As can be seen in the Fourier analyses of the temperature data recorded (Fig. 8 right) the signal amplitude at the chosen frequency is very clear.

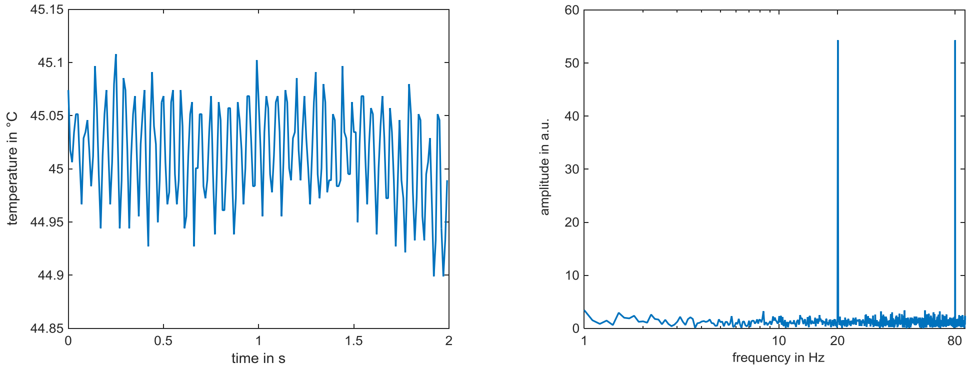

Fig. 8. *20 Hz thermal signal from the specimen surface recorded with IR camera (left) and Fourier analysis thereof (right)*

Results of the quantitative measurements will not be shown here, because the direct correlation of the phase angle and the coating thickness was not possible at this moment. This is, because the ceramic material is to some extent transparent in the mid-wave infrared.

4. Conclusion

While the VCSEL array is supposed to replace both flash and halogen light sources and consequently combine these two regimes into one single testing set-up, it also provides solutions for new applications. The advantages of the spectral separation of the light source and the thermal imaging system have been thoroughly demonstrated. While typical lock-in thermography with optical excitation can already be performed to a good degree without most of the reflection artefacts, these will need either long-wave detectors or suitable filters. On the other hand, the optically excited lock-in thermography testing of blank metal parts was almost impossible up to now without an appropriate laser source. The basic performance for replacing standard (lock-in) equipment has been proven with several generic experiments. Halogen lamp and VCSEL excited tests provide identical measurement results for typical parameters.

Multiplex photothermics for fast characterization of material thickness or thermal diffusivity mapping will allow for new industrial applications like quantitative thickness mapping of thermal barrier coatings of turbine blades. The VCSEL's technical potential has been demonstrated, however, first quantitative results have yet to be produced. An improvement to the measurements of the infrared-transparent ceramics will be made by applying a very thin graphite coating of homogenous thickness that will provide a distinct surface for emission of radiation.

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