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LASER INDUCED LAMB WAVE GENERATION FOR STRUCTURAL HEALTH MONITORING OF CARBON FIBER REINFORCED POLYMERS

Ron Sebastian
Institute for Composite Materials
Kaiserslautern, Germany

Benjamin Kelkel
Institute for Composite Materials
Kaiserslautern, Germany

Martin Gurka
Institute for Composite Materials
Kaiserslautern, Germany

Tobias Traub
Photonik-Zentrum Kaiserslautern e.V.
Kaiserslautern, Germany

Johannes L'huillier
Photonik-Zentrum Kaiserslautern e.V.
Kaiserslautern, Germany

ABSTRACT

In this paper we present an innovative concept for the excitation of guided acoustic waves (lamb waves) in carbon fiber reinforced polymers (CFRP). The idea is to add this external signal generation to a passive structural health monitoring system (SHM), using the now active system for nondestructive testing (NDT). The whole system consists of piezoelectric sensors, embedded in the polymer matrix of the monitored component, the external laser in combination with a scanning device for spatial resolved generation of acoustic waves and a signal processing unit for data analysis. Using laser excitation for lamb wave generation helps to overcome several dis-advantages compared to the use of piezoelectric transducers only: The flexibility in repositioning of the excitation area allows for easy compensation of the strong signal attenuation of CFRP with a minimum number of piezoelectric transducers. The variation of laser wavelength in the range of 1024 to 3500 nm in combination with variation in intensity allows for a selective coupling of the acoustic waves either into the matrix or in the C fibers. Using piezoelectric transducers for detection only, omits the need for a large number of high-voltage amplifiers for signal generation. In this contribution we present first results of a systematic investigation of the effective generation of lamb waves in CFRP. In addition to the variation of the wavelength of the laser, the intensity was varied too. A potentially damaging influence of the laser radiation on the CFRP material was investigated.

INTRODUCTION

With an annual growth rate of 8.1 % over the last 5 years CFRP has become an important material for effective lightweight design [1]. The high specific strength and stiffness along with the excellent corrosion and fatigue resistance justifies the use of CFRP and promotes its introduction in primary structures of civil aircrafts (A350, B787), wind turbines (G128-5.0 MW, V90-3.0 MW) and passenger cars (BMWi series). As a composite material, CFRP allows for a load-conforming design by adjusting matrix material properties, type of carbon fiber, its lay-up as well as manufacturing process. Whereas this flexibility favors the use of CFRP for highly loaded structures on one hand, it is also responsible for the need and complexity of thoroughly inspection and its sensitivity for several damage scenarios on the other. Considering the sensitivity of CFRP to impact loading, the potential formation of damage has to be accounted for inevitably, leading to high knock-down factors in the design and the need for extensive non-destructive testing during production and service of CFRP structures. In order to overcome the amount of in-service testing, emphasis has been placed on the development of Structural Health Monitoring systems that utilize integrated sensor networks to reveal real-time information on the condition of a structure during service. These networks can be built up from strain gauges, piezoelectric sensors, fiber bragg gratings or comparative vacuum monitoring sensors utilizing different physical phenomena and diagnostic methods for the indication of damage [2]. A reliable SHM system would not only increase the confidence in CFRP and thereby support the lightweight design but also allow the shift from time- towards condition-based inspection, hence reducing downtime and lowering costs for operation and maintenance.

One promising candidate for the realization of a passive SHM system is the acoustic emissions (AE) approach. AE testing relies on the detection of elastic waves that origin from the development of flaws like cracks and delaminations inside the device under test. In plate-like structures (thickness of the plate is in the order of the wavelength) these waves are constrained by the upper and lower boundary of the structure, leading to guided waves (also known as Lamb waves) that can travel considerable distances, even in CFRP. The fundamental modes of lamb waves (a symmetrical mode S0 and an asymmetrical mode A0) are coexistent but vary in the associated displacement, velocity and attenuation. By integrating a network of piezoelectric sensors onto a structure it is possible to not only realize the detection of the damage event itself but also to trace its position and describe its nature by tracing the signal characteristics of incoming Lamb waves in time and frequency domain [3, 4]. However, since acoustic emissions emerge and disappear with events of damage formation and growth, there is no possibility for on demand verification of the status of the component with such a passive system.

This can be overcome by incorporating an active element in the system for excitation of Lamb waves, which allows for on demand validation via Acousto-Ultrasonic Testing (AUT). In AUT the interaction of Lamb waves with damage is studied in a pitch-catch configuration. Due to their high sensitivity to structural discontinuities, Lamb wave propagation will be affected by flaws, resulting in considerable changes in wave attenuation, velocity and displacement [5]. Instead of integrating the active component in the online SHM system, this study suggests the use of an external source for an offline inspection method that utilizes the preexistent network of piezoelectric sensors for a cost-efficient NDT. The external source is realized by means of a pulsed Nd:YAG laser that is capable of inducing ultrasonic waves via the thermoacoustic effect. Compared to common ultrasonic testing via piezoelectric transducers, laser generated ultrasound is independent of couplant and angle of incidence, thereby allowing for automated testing of complex shaped parts [6]. Whereas extensive work has been done in the optimization of Laser Ultrasonic Testing (LUT) [7–10] less attention has been spent to the field of laser based AUT. This paper addresses this need by a study on the effect of laser wavelength and pulse energy on the generation of lamb waves in CFRP, following a hybrid approach of combining a passive SHM system with a noncontact NDT method.

EXPERIMENTAL

The experimental setup consists of a MIR laser in combination with two optical parametric oscillators (OPO) in tandem configuration. The fundamental pump wavelength is 1064 nm generated by a pulsed Nd:YAG laser (Spectra-Physics, GCR-150). The pulse repetition rate is 10 Hz, while the pulse length is 12 ns; resulting in a maximum energy of 0.45 Joule per pulse. Depending on the wavelength needed for US generation, one or two additional OPO stages are placed behind the laser source as shown in Figure 1. Main feature of this setup is the broad range of possible wavelengths and impulse energies.

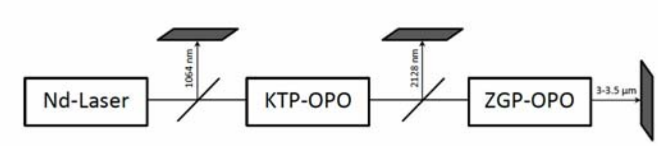

Figure 1: Laser configuration

The first OPO stage consists of a Potassium Titanyl Phosphate (KTP) OPO and doubles the incoming wavelength. An additional Zinc-Germanium-Diphosphide (ZGP) OPO is used for tuning the wavelength of the output laser beam between 3000 and 3500 nm wavelength. Detailed information regarding the laser setup can be found in [11].

For the CFRP test specimen, we used a unidirectional layup of 4 layers (Toray Carbon Fibres America Inc, Type T700S) in combination with XB3585 resin and XB3458 curing agent supplied by Huntsman International LLC. Resin transfer molding resulted in a plate thickness of 2.3 mm with a fiber volume content of approximately 50%. The plate dimensions were 200x300 mm².

For signal acquisition a Macro Fiber Composite (MFC) 2814 (Smart Material Corp.) was used in combination with a Type 5017B multichannel charge amplifier (Kistler Instrumente AG). Due to their geometric design and internal structure MFC sensors are inherently capable to acquire symmetrical S0 mode as well as asymmetrical A0 mode lambwaves with high sensitivity, therefore giving excellent signal characteristics and good signal-to-noise ratio for determination of lambwave signals. Data Aquisition was done with a PXI system (National Instruments GmbH) using a PXI-6281 data acquisition (DAQ) module. Sample frequency was constantly set to 600 kHz with respect to the cut-off frequency of the charge amplifier (-3dB @ 200 kHz). The basic test setup is given in Figure 2. The MFC sensor had to be grounded at its negative terminal to the CFRP plate in order to avoid the pick up of environmental noise. Data evaluation was done within a self-programmed LabView environment (National Instruments GmbH).

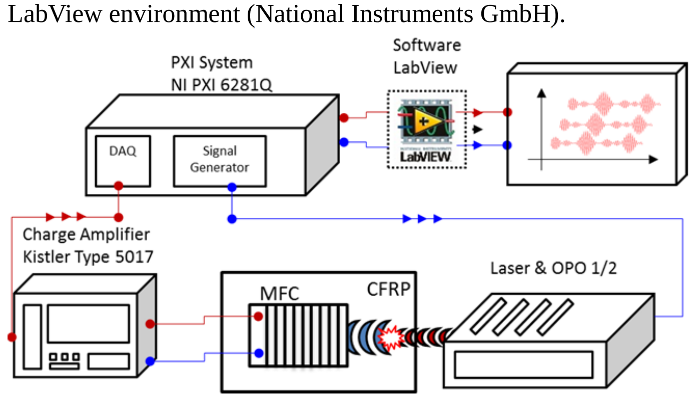

Figure 2: MFC sensor setup

To achieve the highest sensitivity, the MFC sensor was applied with its PZT fibers aligned parallel to the fiber orientation in the CFRP plate. In order to obtain a good signal-to-noise ratio, the area of acoustic wave excitation was chosen at a distance of approx. 10 mm towards the edge of the sensor.

For all measurements at least 10 pulses were accumulated at a repetition rate of approx. 1 Hz. Averaging for determination of the peak amplitude of the acoustic wave was done over at least 5 pulses for each data point. Additionally, long-time tests were conducted for several laser intensities and wavelengths at a 10 Hz repetition rate over a time period of 10 minutes, in order to evaluate a possible damage occurring in the CFRP caused by laser excitation. Laser intensity was chosen according to results of a first test series. Subsequently, the surface of the CFRP was characterized using a white light profilometer (WLP) (MicroProf 100, FRT, Fries Research & Technology GmbH).

RESULTS

Acoustic signal magnitude as a function of laser intensity and wavelength

Laser pulse energy was increased in 5 steps at the wavelength of 1064 nm. A photo acoustic signal could only be determined for the highest pulse energy at 96 mJ. In Figure 3 shows a typical photo acoustic signal acquired by the MFC sensor. Two signal peaks are clearly determinable approx. 800 ms apart.

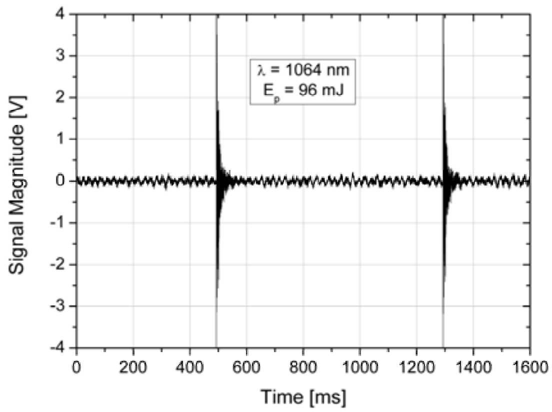

Figure 3: Typical plot of acquired signal (time domain)

As shown in Figure 4 it is obvious that only for the highest impulse energy a clear photo acoustic signal could be acquired. At lower energies, an acquired signal could not be separated from the noise floor. According to [12], the damage threshold of CFRP can approximately be found at 0.5 GW/cm². In our experiment the laser was focused on a spot of 1.05 mm diameter, with pulse duration of 14.2 ns. Therefore the resulting maximum peak power density of 0.77 GW/cm² is clearly higher than damage threshold from literature. Even a few laser impulses led to visible, severe damage. The use of 1064 nm wavelength to create a photo acoustic signal within CFRP seems to be limiting.

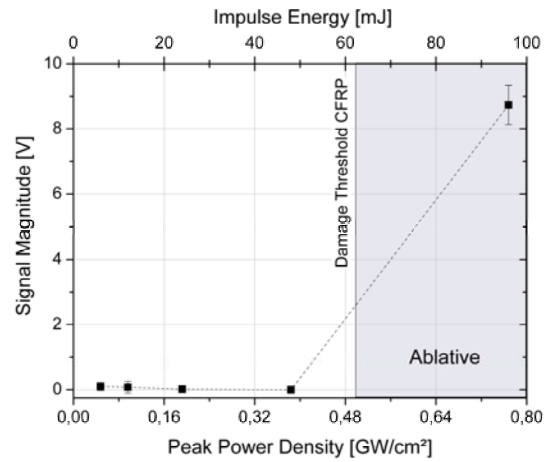

Figure 4: Piezo sensor signal magnitude vs. laser power density for 1064 nm

For a laser wavelength of 2128 nm, the pulse energy was varied from 0.06 up to 46 mJ. Again, only for the highest pulse energy of 46 mJ a photoacoustic signal could be detected (s. Figure 5). In contrast to the experiments using 1064 nm wavelength, the peak power density is still below the damage threshold. A thorough examination of the CFRP specimen revealed no severe damage (ablation or melting) but still a slight laser-induced change in surface color could be found. In order to clarify possible critical changes in material structre additonal test series with long-time laser exposition were conducted and analysed subsequently.

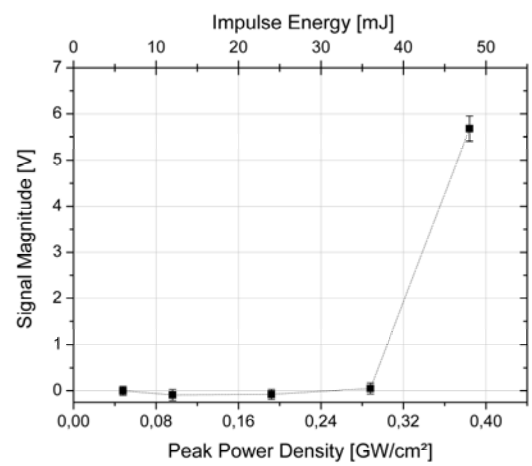

Figure 5: Piezo sensor signal magnitude vs. laser power density for 2128 nm

Using the KTP and ZGP OPO in tandem configuration, it was no longer possible to vary the laser wavelength and pulse energy independantly. The pulse energy increased from 1.5 to 6 mJ for wavelength from 3000 to 3500 nm, as shown in Figure 6. For all investigated wavelength and energy combinations photoacoustic signals were obtained.

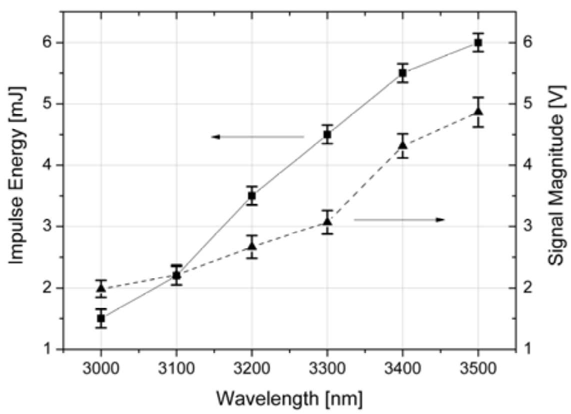

Figure 6: Piezo sensor signal magnitude and laser impulse energy as variation of laser wavelength (3000-3500 nm)

For all laser wavelengths and intensities no damage of the CFRP plate could be found. Peak power densities for all wavelength-energy combinations were below 0.06 GW/ cm², well below the expected damage threshold of 0.5 GW/cm².

To compare the efficiency of photoacoustic signal generation for all wavelength in the range from 1064 – 3500 nm, all acoustic signals were normalized to a laser pulse energy of 1mJ per pulse (s. Figure 7).

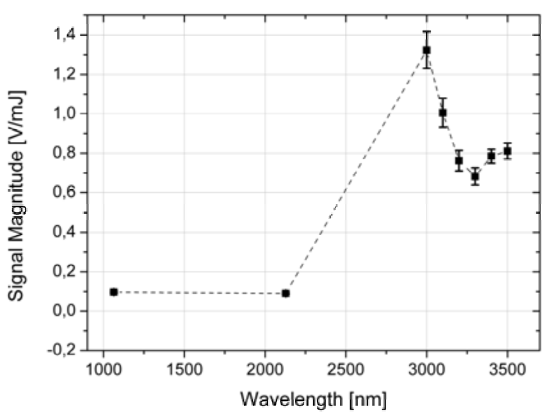

Figure 7: Signal magnitude normalized to 1 mJ

The clear maximum in photo acoustic signal excitation for a laser wavelength of 3000 nm can be understood, if one compares the signal magnitude, given in Figure 7 with an absorption spectrum of the epoxy matrix polymer as it is given in e.g. [10]. The epoxy polymer is nearly transparent for the laser light at 1064 and 2128 nm wavelength but exhibits a strong absorption maximum around 3000 nm. Therefore, the mechanisms of acoustic signal excitation must be due to thermal expansion in the epoxy matrix polymer rather than due to laser energy absorption in the C fibers, which exhibit strong absorption for all laser wavelength in the investigated range.

Figure 8 shows the cross section of the investigated layer structure of the CFRP sheet. The top layer of epoxy matrix was measured to be ~80 µm in thickness. The low thickness together with a low absorption rate for 1064 and 2128 nm wavelength enables most of the laser energy to hit the first layer of C fibers, where it is absorbed and converted into heat energy. C-fibers exhibit only very low coefficients of thermal expansion, in the range of -1 10^{-6} /K, compared to 60 10^{-6}/K for epoxy polymers [13]. A photoacoustic signal therefore is only generated for high intensities, when the C-fibers heat up the matrix polymer. At 3000 nm the situation is different: most of the laser energy is absorbed directly in the epoxy matrix polymer, with an expected optical penetration depth of less than ~30 µm [9], leading to significant acoustic signal excitation.

The CH-bonds within polymer matrix are responsible for high absorption ratio within this wavelengths and are common for all kinds of epoxy resin [14].

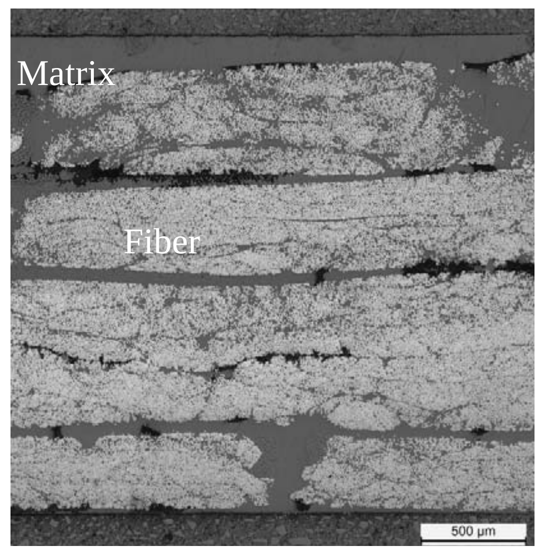

Figure 8: Cross section cut of the CFRP sheet

In [10] and [15] it is claimed, that the photo acoustic effect generated by a “buried ultrasonic source” is dominating over a surface ultrasonic source. Therefore, it was concluded, that a high absorption rate of the matrix polymer must lead to less acoustic excitation.

From our own experiments this statement cannot be confirmed. Especially the very high energy densities which are necessary to obtain a good photo acoustic effect at 1064 and 2128 nm wavelength are in discrepancy. For these wavelengths the matrix material can be assumed nearly transparent, with a transmission >90% [8]. According to the above-mentioned publications, a strong signal excited from the C fibers, acting as a “buried source” should be obtained.

To take a closer look on the mechanisms underlying photo acoustic generation within CFRP, we used two different samples in the same setup as described above.

(1) a thin plate made of pure epoxy polymer and

(2) .a bunch of carbon fibers where one side, outside the laser excitation area, a MFC sensor was attached using epoxy as adhesive were investigated at 3000-3500 nm wavelength.

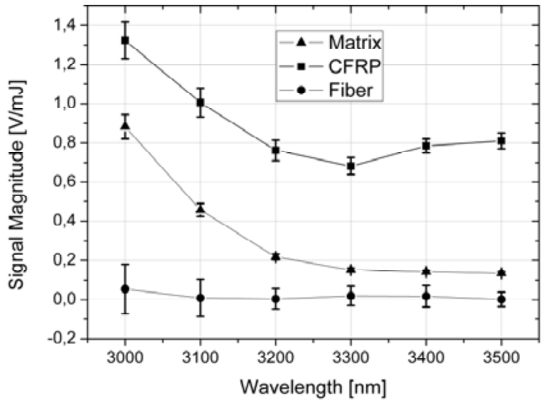

Figure 9: Signal magnitudes of CFRP composite and its components Matrix and Fiber normalized to 1 mJ

The results in Figure 9 reveal the main contribution for the acoustic signal is due to the epoxy matrix polymer. While the acoustic signals measured on the pure fiber sample are very weak, the signal magnitude and also its dependency on laser wavelength is comparable to the measurement of the whole CFRP sample.
Taking into account the distinctive behavior of lamb waves in contrast to the normal longitudinal ultrasonic waves in a pitch catch setup the difference to the findings in [10] and [15] can be explained: Lamb waves are a superposition of longitudinal and transversal waves, traveling in plane of a thin walled specimen. Therefore it is a very efficient way to excite their longitudinal component, e.g. by "in-plane" thermal expansion. If, in contrast, the US-wave is traveling in thickness direction, it is more efficient if its excitation is beneath the surface. There are no losses due to reflection at the surface and an additional enhancement due to the backing material behind the source.

A summary of the changes in surface topography from continuous laser irradiation of CFRP surface is given in Figure 10.

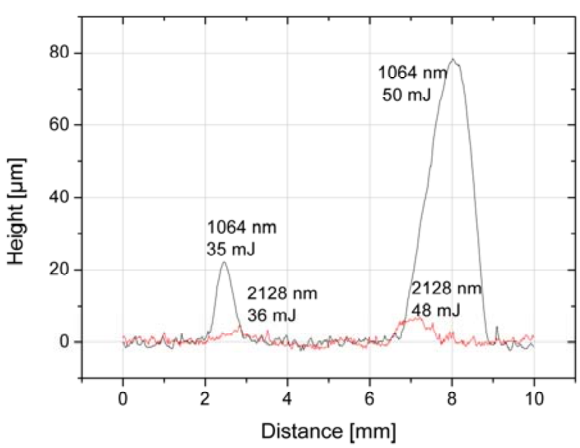

Figure 10: Surface profiles of irradiated specimen

The cross section views of the WLP scanned surface clearly show the tendency of larger damage for rising energy at lower wavelengths. Surface section view for 3500 nm is not given since it only shows average surface roughness. The induced heat for high energy levels at low wavelength lead to a de-bonding between C fibers and surface matrix layer. This is caused by the heat present on the fiber surface. This results in an enclosed air bubble between both.

CONCLUSION

Figure 11 gives a summary of the experimental results. The acoustic signal magnitude for lamb wave excitation is plotted versus laser pulse energy respective peak power density for three different laser wavelength (1064, 2128 and 3500 nm). While for 3500 nm wavelength only 6 mJ pulse energy is sufficient to give an acceptable signal to noise ratio, for shorter wavelength the pulse energies have to be 48 mJ (2128 nm) and 96 mJ (1064 nm) to give a similar acoustic signal magnitude. But then the signal excitation is no longer thermo elastic, damage to the CFRP material must be considered. Beginning with matrix degradation and slight ablation for 2128 nm; and 48 mJ pulse energy a reduction of laser wavelength to 1064 nm and 96 mJ leads to strong ablative damage.

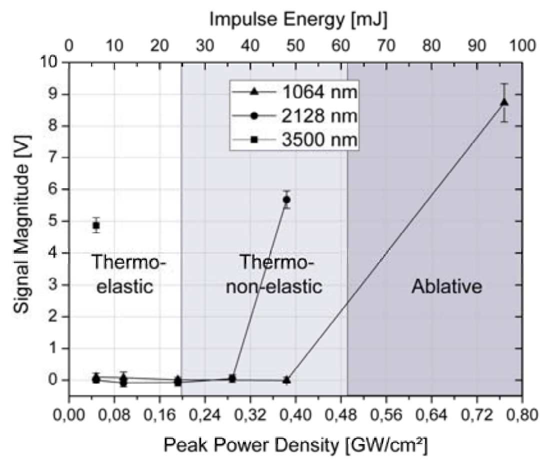

Figure 11: Summary of signal magnitudes as function of wavelength and impulse energy

The main mechanisms responsible for photo acoustic excitation of the acoustic lamb waves within the specimen can be seen in a large thermal expansion of the epoxy matrix polymer due to strong absorption of the laser beam near the surface of the CFRP material. For propagation of these guided waves along the specimen a strong coupling of the longitudinal component together with the transversal one has to take place in the composite material. Therefore the use of laser wavelengths with good absorption factor by the matrix surface together with strong fiber matrix interaction leads to an acoustic surface source, enhancing the guided acoustic wave propagation.

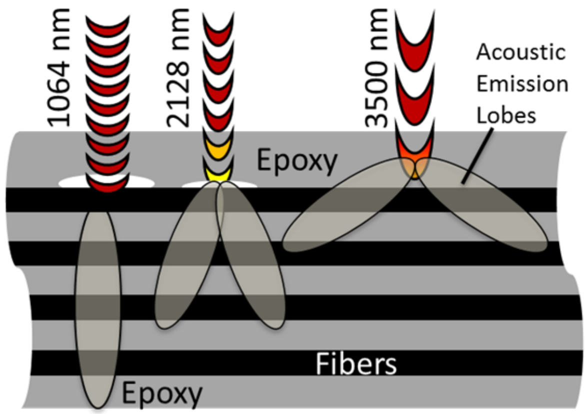

Figure 12: Absorption and photo acoustic mechanisms

An schematic overview of the main absorption positioning of the laser pulse is given in Figure 12 as well as resulting acoustic wave propagation according to [6].

The results lead to three important statements:

- US excitation of longitudinal Lamb waves with a laser pulse is most efficient for a surface source configuration based on thermal expansion of matrix material.
- Although highly absorbing (even at 1064 nm), carbon fibers give worse signal response resulting from a negative thermal expansion coefficient in fiber direction
- Damage occurs for short wavelengths (1064 & 2128 nm) within the fiber-matrix interface due to the "hot" fiber surface.

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