A new fiber-optic non-contact compact laser-ultrasound scanner for fast non-destructive testing and evaluation of aircraft composites

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Laser ultrasonic (LU) inspection represents an attractive, non-contact method to evaluate composite materials. Current non-contact systems, however, have relatively low sensitivity compared to contact piezoelectric detection. They are also difficult to adjust, very expensive, and strongly influenced by environmental noise. Here, we demonstrate that most of these drawbacks can be eliminated by combining a new generation of compact, inexpensive fiber lasers with new developments in fiber telecommunication optics and an optimally designed balanced probe scheme. In particular, a new type of a balanced fiber-optic Sagnac interferometer is presented as part of an all-optical LU pump-probe system for non-destructive testing and evaluation of aircraft composites. The performance of the LU system is demonstrated on a composite sample with known defects. Wide-band ultrasound probe signals are generated directly at the sample surface with a pulsed fiber laser delivering nanosecond laser pulses at a repetition rate up to 76 kHz rate with a pulse energy of 0.6 mJ. A balanced fiber-optic Sagnac interferometer is employed to detect pressure signals at the same point on the composite surface. A- and B-scans obtained with the Sagnac interferometer are compared to those made with a contact wide-band polyvinylidene fluoride transducer. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4868463>]

I. INTRODUCTION

Laser ultrasound (LU) has a long history, starting first with laboratory devices and now including commercial systems for field applications.^{1–9} All practical LU systems must optimize both transmit (pump) and receive (probe) paths for a given application. Transmit pulses are usually generated through laser-induced, non-stationary heating of a target and its subsequent thermal expansion.¹⁰ When the laser pulse duration is varied from ~100 ps to ~100 ns, generated pressure amplitudes can achieve tens of or even one hundred of MPa, with relatively low (tens of mJ) laser pulse energies.^{11,12} A unique feature of laser generated ultrasound (US), or optoacoustic (OA) signals, is their unipolar or bipolar¹⁰ impulse response, which cannot be efficiently duplicated with piezoelectric excitation. Ultimately, the temporal profile of optically generated acoustic signals mimics the laser pulse envelope, i.e., it can be perfectly Gaussian.^{9,10,13} For near unipolar excitation, the ultra wideband frequency spectrum does not have a true central emission frequency. Using the $1/2$ or $1/e$ level to characterize the mean frequency, the time duration of an OA signal is typically three to five times shorter than that of a conventional US pulse with matching mean frequency which provides much better spatial resolution.

Detecting OA signals is more difficult. Often, a piezoelectric transducer acts as the detector even though it requires contact with the specimen under study. Conventional piezoelectric transducers do not have a compact impulse response and, therefore, limit the potential axial resolution of

broadband OA signals. This problem can be overcome using ultra wide-band piezoelectric transducers designed specifically for OA signals.^{14–17} Transducers constructed from polyvinylidene fluoride (PVDF) films of varying thickness operating in an open circuit regime¹⁴ represent the gold standard for ultra wideband detection, even producing bandwidths approaching 150 MHz. Other contact approaches have been used which may approach the performance of PVDF transducers. For example, contact optical resonators show some promise for wideband detection.^{18–22} Also, capacitive micromachined ultrasound transducers (CMUTs) have been built with wide bandwidth and high sensitivity.^{23–25} Although all of these broadband approaches may be effective OA signal detectors, they cannot be used for a large number of non-destructive testing and evaluation (NDT&E) applications where acoustic contact is not desirable, and sometimes not even allowed.

Optical detection represents the primary approach for non-contact systems. Advances have been made both for materials evaluation and biomedical applications, as detailed in a series of reviews.^{1,3,4,26,27} For example, all-optical systems with high sensitivity have been developed to characterize coatings used on materials (see, for example, Refs. 6 and 7, and 28–30). Here, non-contact laser interferometry has no alternative since most modern coatings cannot be subjected to any contact, particularly immersion.

NDT&E applications require sensitive detection of bulk waves. Optical detection is often limited because speckle structure in the reflected probe beam limits the amount of light that can be collected into a typical interferometer, such as a Michelson. Seminal work was performed by J.-P. Monchalin's group.^{2,5,31,32} A design by this group based on a confocal Fabry-Perot interferometer significantly reduced

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the influence of the light collection system. Other approaches aimed at minimizing the effects of speckle structure include modifications of a Sagnac interferometer^{33–38} and interferometer schemes employing photorefractive crystals.^{31,39–41} However, the detection sensitivity of all these optical techniques does not approach that of a well-designed, contact piezoelectric transducer.

The work described below focused on increasing both the sensitivity and efficiency of LU systems for non-destructive evaluation of fiber reinforced composite materials used in the aerospace industry. The overall goal is to overcome some of the challenges and disadvantages of current LU approaches:

- (i) LU systems are usually cumbersome and not highly portable because solid crystal or CO₂ lasers are used for OA signal generation;
- (ii) non-contact systems are expensive compared to conventional US systems;
- (iii) optical interferometers are usually very sensitive to environmental noise, difficult to adjust, and need stabilization;
- (iv) detection sensitivity is strongly affected by roughness at the probing surface;
- (v) and, most importantly, overall system sensitivity is usually a few orders of magnitude smaller than that of contact wideband US detectors.

Our approach leverages recent progress in fiber and diode laser systems and telecommunication optics, and addresses a number of the limitations of non-contact LU systems commonly used for NDT&E of composite materials in the aerospace industry. We will demonstrate below that bulky, high-energy, low repetition-rate lasers, the standard for most LU systems for over a decade, can be replaced as the OA source (pump) with modern, portable, and inexpensive fiber or diode-pumped high repetition-rate lasers. They deliver a few mJ per shot and can operate at high repetition rates, easily meeting the kHz level of conventional ultrasound (see, for example, Ref. 42). Using this type of laser in an LU system can dramatically increase scan speed, make the system much more compact, enable more flexible designs, and reduce overall system cost.

Most non-contact optical detection schemes rely on some form of interferometry (probe). Recent advances in continuous wave (CW) fiber lasers (for highly coherent sources) and super luminescent diodes (SLD) can be exploited for more sensitive detection based on optical interferometry. Both sources are low noise, compact, and quite inexpensive. Below we show that an SLD is nearly ideal when a relatively low coherence source is required.

Most interferometers are highly sensitive to environmental noise. Thermal fluctuations from any source, or mechanical and acoustic vibrations, can change resonance conditions. Therefore, feedback is required to stabilize detector sensitivity. A number of stabilization algorithms have been developed, but all are relatively slow, cannot provide complete rejection of background noise, and significantly increase the size, complexity, and cost of the interferometer.^{1,3,4}

For LU inspection of real composite structures used in the aerospace industry, reflections from rough surfaces must be processed effectively. To handle rough surfaces and simultaneously minimize the effects of environmental noise, we employed a Sagnac-based interferometer^{33–37} measuring vibration speed instead of displacement. This approach has no reference arm. In addition, a differential Sagnac detector is relatively insensitive to surface roughness over the extent of the beam probing that surface. In contrast, an interferometer with a reference arm using a highly coherent source, such as Michelson or conventional Fabry-Perot schemes, is highly sensitive to surface heterogeneities producing speckle structure in the reflected beam.

Most schemes utilizing a reference beam use only the central speckle for stable operation to minimize large variations in beam intensity and phase. This problem can be partially eliminated by finely focusing the probe beam onto the sample surface, but it does not help in all cases and requires very fine focus adjustment. Our interferometric detector (Sec. II) also includes focusing of the probe beam onto the sample surface for better light collection from a rough surface. However, both interfering beams reflect from the same surface and, therefore, no stabilization is required. Changes in the reflected beam mode structure from position to position do not alter ultrasound signal characteristics and only affect overall signal amplitude.

In addition to robustness, sensitivity determines overall detector performance. The fundamental sensitivity limit is determined by the Johnson-Nyquist noise associated with acoustic detection over a finite spatial aperture and signal bandwidth no matter the modality.^{2,3,12,18,19} As will be demonstrated below, the Sagnac-based, non-contact detector developed for our LU system approaches the Johnson-Nyquist noise limit and is as sensitive as the best acoustic detectors operating over the same detection area and signal bandwidth.

II. MATERIALS AND METHOD

A. Samples of fiber reinforced composites

Samples used here came from Boeing Research & Technology and represent typical fiber reinforced graphite-epoxy composites employed to construct aircraft at Boeing. The LU system described below scanned a number of samples of varying thickness with different defects. Here, we demonstrate how the LU system can function for this class of materials using results from a single representative sample. It is 3.6 mm thick and contains nineteen (19) individual layers (i.e., plies). An artificial defect made from a 20 μ m thick brass foil was embedded in the composite at a depth close to the middle of the sample and parallel to the sample surface.

As noted above, surface roughness can severely degrade the sensitivity of interferometry. The surface roughness of the sample used for generation/detection of ultrasound in this study was quantified using conventional profilometry (Taylor&Hobson, Taylor&Hobson, Form Talysurf Series 2, model 120i, <http://www.taylor-hobson.com>). A microphotograph of that surface is shown in Fig. 1. Clearly, the

FIG. 1. Micro-photograph of a typical small area (1.5 mm $\times$ 2 mm) of the composite sample used in these studies. The mean height of the roughness profile is about 4 μ m.

composite surface is far from mirror-like. The mean height of the roughness profile is about 4 μ m, i.e., more than two wavelengths, which certainly decreases probe beam reflectivity.

B. All optical system design

The overall approach is quite standard for LU inspection, as illustrated in Fig. 2, but has several important, differentiating features. First, a compact, inexpensive fiber laser operating at quite low pulse energies (0.6 mJ) but at very high pulse repetition rates (variable up to 76 kHz) is used for OA signal generation instead of bulky, expensive, low repetition-rate CO₂ or solid crystal lasers. Thus, our approach uses small energies, narrow pump beams, and high repetition rates rather than low repetition rates, high-energy laser pulses, and wide pump beams. The pump laser head is 1 cm in diameter and 15 cm long (cylinder) connected to the power supply box with a 3 m long fiber bundle. This design is very flexible in positioning the laser

FIG. 2. Main components and operating principle of the all-optical pump-probe system for NDT&E of composite materials. A compact, very high repetition-rate (up to 76 kHz) fiber laser with transmit head connected to the fiber laser using a 3 m fiber bundle (in the left corner) irradiates the sample surface with nanosecond laser pulses, inducing OA generation; the receive head connected to the fiber-optic balanced Sagnac interferometer with a PM fiber is used for non-contact US signal detection.

source and makes it relatively easy to meet laser safety requirements.

A convex lens (150 mm focal distance) attached to the pump laser head focuses collimated radiation to the sample, enabling a variable laser beam diameter at the surface by simply changing the distance from the lens to the sample. The OA signal amplitude is proportional to laser fluence, i.e., to the laser energy concentrated in a unit surface area.¹⁰ On the other hand, diffraction loss for a propagating wave produces pressure amplitude inversely proportional to the beam radius squared⁴³

$$p(z) = \frac{p(z=0)}{\sqrt{1+z^2/l_d^2}} \sim \frac{E_0}{r_0^2 \sqrt{1+z^2/l_d^2}}, \quad (1)$$

where E_0 is the energy of the laser pulse, z is the propagating distance, $l_d = \frac{\pi r_0^2 f_{ac}}{c_{ac}}$ is the diffraction length, f_{ac} is the frequency of the US wave, r_0 is the radius of the laser beam at the sample surface, and $c_{ac} \approx 3000$ m/s is the speed of sound in the sample.

For depths where $z \gg l_d$, all curves match closely, but in the subsurface region of the sample (in the near field), the laser beam diameter can be optimized to increase OA signal amplitude. The samples studied here are 3.6 mm thick. The laser beam radius was chosen to be $r_0 = 0.75$ mm to avoid strong decay of the US beam with depth due to diffraction.

Several key laser parameters, such as pulse duration, pulse energy, and pulse repetition rate, are under software control. We used 0.53 mJ at 60 ns pulse duration. Finally, the pulse repetition rate must be carefully selected based on the mechanical scan rate of the pump laser source. For example, a laser operating at 0.53 mJ with a 76 kHz pulse repetition rate would burn the sample immediately if fixed at a certain position, i.e., without scanning. The safe pulse repetition rate at this energy is determined by the heat release process, which for the class of samples used here is ~ 500 Hz with no sample scanning. However, the pulse repetition rate can be greatly increased when the sample moves, and is limited practically by the maximum translation speed of the scanner.

Pump-laser pulses are delivered at an oblique angle ($\sim 40^\circ$ from the sample normal), allowing the probe-laser beam to be focused to the same point on the surface. The OA-generated pulse propagates through the sample, partially reflecting from internal structure before reflecting off of the back wall. All transients propagating back to the front wall of the sample are detected with the interferometer described below (Sec. II C). Radio frequency (RF) signals output from the interferometer are amplified over the range of 1–10 MHz (Panametrics, Model 5072PR), digitized to 14 bits by a PCI Express3 analogue-to-digital converter (ADC, GaGe, Model Razor Compuscope RZE-002-300, gage-applied.com), and transferred to a workstation (HP, Model Z820, hp.com) for further signal processing and display. The ADC is triggered by the output of a photodiode (Thorlabs, Model DET 10 A, thorlabs.com) detecting a small fraction of the pump pulse coupled into it. Time zero is set at the moment when the OA pulse was generated at the sample surface, avoiding any jitter induced by pulse-to-pulse laser instability.

Composite samples are positioned on a 2D translation stage for all imaging studies. The X-axis is driven by a stepper motor controller (Thorlabs, Model LNR50DD) with variable speed control up to 8 mm/s. The sample is moved continuously during scanning, where the maximum travel distance is 50 mm (maximum allowed travel distance for the stage). Position accuracy in the X-direction is also determined by the stage and is better than $2\ \mu\text{m}$. At each position during scanning, a digital RF A-Scan is recorded after each laser firing. Each A-scan corresponds to the distribution of US transients reflected by the composite structure back to the detection point, i.e., along the Z-direction. Sample translation along the X-axis forms a B-scan image corresponding to the distribution of US scatterers in the XZ plane. Single A-scans in a B-scan are stitched together without any beam forming procedure or signal interpolation. Note that the scanning procedure is not novel here. The translation stage was selected primarily for its accuracy. The ultimate scan speed of an overall LU system is limited by the maximum pulse repetition rate of the pump laser. For the 76 kHz maximum rate of the fiber laser used here, the ultimate scan rate of inspection can be much higher than the 8 mm/s limit of the current system.

C. Fiber optic Sagnac interferometer with balanced signal detection

An optical interferometer is a key component of all LU systems. To meet the design goals of Sec. I, we developed a fiber optic Sagnac-based interferometer with a balanced detection scheme using only fiber components. Most fibers in the interferometer are polarization maintaining and virtually insensitive to both mechanical vibrations and fiber twisting. This makes interferometer design very flexible because fiber optical elements can be placed on any supporting surface, rather than needing to be solidly attached to an optical table. Once tuned, there is no need for further adjustments or any kind of feedback to stabilize operation. Overall, this is a very rugged design appropriate for typical field operations in the aerospace industry.

1. Operating principle

The output of an interferometer is directly related to the interference between two independent optical beams. The advantage of the Sagnac approach is that no reference beam is required. Both interfering beams come from the same surface reflection, making the interferometer stable to any environmental vibrations and temperature fluctuations. Thus, this interferometer does not require feedback, a critical issue for overall system stability, reliability, and speed. Furthermore, no reference arm makes the Sagnac interferometer insensitive to the speckle structure of the probe beam reflected from a rough composite surface. Sample roughness, therefore, only affects the light power coupled into the interferometer.

To produce two independent beams, laser radiation initially linearly polarized along the slow axis is rotated by 45° using a polarization controller (Thorlabs, Model FPC020) and then divided into two arms with a polarization beam splitter (PBS1 in the drawing). These two arms have different lengths

so that two optical waves appear at the next polarization beam splitter (PBS2) with a fixed delay. The delay determines the maximum detectable US frequency and can be easily adjusted by changing the longer fiber to a different length. Matching the fiber length to the desired frequency band (10 MHz in our case) maximizes detection sensitivity.

PBS2 combines the delayed beams into one fiber, maintaining their polarizations. The collimator (receive head in Fig. 2—see detail below in Fig. 3(a)) finally focuses the probe radiation onto the sample surface. The receive head should effectively focus probe radiation to the sample surface and couple backscattered radiation back into the $8\ \mu\text{m}$ PM fiber with maximum efficiency. Although simple in design, manufacturing of the head (CourierTronics, couriertronics.com) must be very precise. It contains two lenses, one collimates outgoing radiation from the fiber and the other, with a high NA of 0.5, focuses radiation onto the surface. There are a few additional components between the lenses: a wave separator (Altechna, altechna.com) to propagate 1550 nm radiation without distortion and block any pump laser radiation (1064 nm) at the same time; and a high aperture (40 mm) quarter wave (QW) plate (Altechna) exchanging the polarization of the two interfering beams after reflection from the surface.

FIG. 3. (a) Diagram of the receive interferometer head and (b) the radial distribution of the probe beam in the focal area of the interferometer, obtained with a knife-edge technique (dots—measured, red curve—fitted with a Gaussian function).

Radiation coupled back to the fiber contains two delayed waves, similar to incident illumination conditions but with exchanged polarizations. The wave that propagated initially through the short arm now propagates through the long arm on the way back, and vice versa for the second beam. These beams have no delay when they reach PBS1 and finally interfere within the polarization controller.

The beams are split one last time with PBS3 to dramatically reduce interferometer noise and make the system insensitive to thermal lens⁴⁴ effects induced by the pump laser. When their powers are equal and the polarization state is 270°, the polarization sensitive photocurrents will have opposite signs at the inputs of a balanced photodetector. Subtracting the signals within the balanced photodiode (Thorlabs, Model PDB 420 C-AC) finally gives a photocurrent virtually insensitive to laser induced changes of the sample refractive index, and other stationary polarization insensitive noise. This makes it possible to work with very low light power reflected back by a rough sample surface. Note that the sensitivity of regular (non avalanche) photodiodes is much less than that of avalanche ones, but they provide much better inherent dynamic range, greater than 50 dB.⁴⁵ Overall, balanced detection provides sensitivity equivalent to that of avalanche photodiodes, but with much better dynamic range.

As noted above, the Sagnac scheme registers the difference between two surface displacements recorded at close time instants determined by the propagation delay in the long fiber arm relative to the short one. Thus, the output is proportional to vibration speed or acoustic pressure. This is another advantage over displacement-based interferometers commonly used in NDT&E applications since a derivative (i.e., high pass filter) operation is not needed. This high pass filtering operation, usually implemented in the digital domain, can reduce the signal-to-noise ratio (SNR) of the detected signal.

The last key feature is that the detection bandwidth is not limited from below and is limited from above by only the difference in fiber arms determining the maximum operating frequency. Therefore, the maximum detectable frequency can be easily varied by changing the long arm fiber length, providing ultra wide-band US detection yet enabling optimal sensitivity over a specified band. For the studies reported below, the operating band was chosen to span 1–10 MHz based on the acoustic properties and geometry of the composite materials under study.

To summarize the operating principle, when there is no pump laser input at the composite surface, the displacement difference between the two interfering optical beams is zero, and the interferometer records nothing. When pulsed laser radiation generates an OA pulse, however, the interferometer detects the laser induced pressure signal, and all other pressure transients reflected back by the composite structure.

2. Probe beam source

A SLD (SLD, Thorlabs, Model SLD1550P-A40) is the source of probe radiation. It operates at a center wavelength of 1550 nm with a bandwidth of 60 nm, well within the

communication range where we can take advantage of the most recent developments in fiber-optic components and devices. Output power was proportional to the current applied to the SLD and can be varied up to 40 mW.

The probe laser is quite low coherence (coherence length is $\sim 40 \mu\text{m}$), a feature removing nearly all parasitic interference inside the interferometer from reflections between connections and, thus, dramatically decreasing system noise. On the other hand, a $40 \mu\text{m}$ coherence length is many times larger than the displacement induced by US transients at the sample surface. An additional polarizer is attached to the SLD to ensure a linearly polarized output. A fiber isolator follows the polarizer to avoid any reflections back to the SLD which could damage the source.

3. Probe beam focal spot

An important issue for any imaging system is spatial resolution. The probe beam diameter (see Fig. 3(a)) determines the minimum size of an acoustic heterogeneity that the Sagnac detector can resolve. A knife edge method⁴⁶ was used for this measurement, where a sharp surgical scalpel was fixed to a 3D translation stage allowing fine translation with $1 \mu\text{m}$ accuracy in all three directions. An energy meter (Ophir, Model 3 A-Rohs, www.ophir-spiricon.com) mounted behind the scalpel recorded all optical power emitted by the SLD and transmitted through the knife edge. The recorded power versus scalpel edge position in the direction perpendicular to the beam normal was differentiated to form the radial distribution of optical power in the focal plane of the probe beam. The resulting curve (see Fig. 3(b)) was fitted with a Gaussian function, which finally yields a $(7.4 \pm 0.7) \mu\text{m}$ focal spot diameter.

4. Impulse response of the Sagnac detector

The detector's impulse response was estimated by inputting an acoustic pulse with a much broader bandwidth than the detector itself and recording the resultant output. The interrogating pulse was created optoacoustically using a strong optical absorber, permanent marker ink, painted on a PMMA plate. Fig. 4(a) presents the measured impulse response (black line) prior to any analog filtering. Clearly, the output has a smooth temporal profile with no sidelobes. Using the full width at half maximum amplitude, the pulse duration, Δt , is 90 ns. This can be easily converted into the axial, Δz , resolution in a material using the speed of sound, c_{ac} , in that material

$$\Delta z = c_{ac} \Delta t / 2, \quad (2)$$

which gives $\Delta z = 135 \mu\text{m}$ for the composite materials under study. The factor of two in (2) corresponds to back-scattered US signals (backward detection mode).

The transfer function is the Fourier transform of the impulse response, as illustrated in Fig. 4(b) (black line) for that of Fig. 4(a). Note that the upper frequency roll-off is determined primarily by the length difference of long and short fiber arms in the interferometer and can be easily tuned by changing the long fiber length. We have limited the

FIG. 4. (a) Impulse response of the fiber-optic Sagnac detector. Black curve corresponds to the OA signal recorded with the Sagnac interferometer without filtration when the target was a PMMA plate covered with the black permanent marker. Red curve shows the recorded RF signal after band-pass (1 MHz–10 MHz) filtering to eliminate low frequency instability and reduce high frequency noise in the system. (b)—corresponding spectra of the signals above. The characteristic frequency of the whole bandwidth signal is 2.9 MHz (at $1/2$ level), but the impulse response is only 95 ns.

acoustic spectrum to about 10 MHz since attenuation in the composite samples used here increases significantly at higher frequencies.

The detector bandwidth, defined as the spectral width at half maximum amplitude, is 2.9 MHz but results in an impulse response only 95 ns long. A typical bipolar pulse produced by a broadband piezoelectric transducer operating at the same characteristic frequency would have a duration about equal to the inverse of the bandwidth, i.e., about 300 ns in this case. The optical detector's tight impulse response is a significant advantage for NDT&E, typically producing a factor of three improvement in axial resolution compared to equivalent contact piezoelectric transducers.

Although the impulse response is quite compact, it has a significant component at zero frequency (i.e., dc). For applications requiring a large signal dynamic range, the dc offset can be a problem because it can limit the dynamic range of all subsequent electronics. This is especially true when there are significant thermal lens effects at a particular point on the rough surface of a composite sample producing a very strong but very low frequency signal.⁴⁴ To

overcome this problem, the interferometer output is high pass (HP) filtered (using the 1 MHz Panametrics cutoff limit for the low frequency edge) prior to amplification and digitization. The resultant signal and its spectrum are illustrated in Figs. 4(a) and 4(b) with the red curves. This operation shifts the characteristic frequency of the transfer function to a higher range (5.2 MHz). Because the filter can be fully characterized, much of the low frequency response can be recovered after digitization using a deconvolution procedure (see below).

D. Auxiliary measurements with a contact PVDF hydrophone

To determine the sensitivity of the proposed interferometer and compare imaging performance with contact piezoelectric techniques, we performed measurements with a home-made ultra wideband PVDF transducer. A water tank 10 cm $\times$ 7 cm in cross section was attached to the front surface of the sample and filled with deionized water (see Figs. 5(a) and 5(b)). The transducer was positioned 20 mm above the sample surface. Scanning of the samples was performed in exactly the same way for the PVDF transducer and optical detector. PVDF transducers represent the gold standard for wide-band ultrasound detection, providing almost uniform spectral response over the operating bandwidth that can produce LU signals with virtually no distortion. The hydrophone used in the current work was made from a 28 μ m thick PVDF film (Precision Acoustics) and operates in an open circuit regime.¹⁴ It is unfocused and axially symmetrical. The diameter of the receiving aperture is 6 mm.

The PVDF transducer was calibrated in the frequency band of 0.1 MHz–50 MHz (see Figs. 5(c) and 5(d)) and showed almost uniform sensitivity in the frequency range of 0.2 MHz–15 MHz (with variations less than 5 dB), completely covering the frequency band of the optical detection system presented above and enabling direct comparison of the two detection approaches. The measured noise equivalent pressure was about 10 Pa over the operating band, 1 MHz–10 MHz, of the Sagnac detector. A more detailed description of the PVDF transducers used for OA signal detection can be found, for example, in Refs. 14–17.

III. RESULTS

A. A-scan signals

Using the samples described in Sec. II A, a large collection of A-Scans was recorded to further optimize the signal processing path for imaging applications. Fig. 6(a) compares typical A-scan signals recorded from a single pump laser firing (i.e., without any averaging) for the Sagnac detector (red curve) and the PVDF (blue curve) transducer. There are no defects in the sample for the region sampled by these recordings. The signals are very similar and provide similar information about the composite structure. Both have a strong periodic component between front- and back-wall signals. This periodic signal corresponds to reflections of the probe signal, generated at the composite surface, by the

FIG. 5. Diagram (a) and photo (b) of auxiliary measurements with an ultra wide-band PVDF transducer. The home-made PVDF transducer was acoustically coupled with deionized water and located at a distance of 20 mm from the surface of a composite sample. All other system parameters corresponded to those for optical detection. The impulse response of the PVDF transducer (c), and its spectral transfer function (d), show an almost unipolar signal profile without sidelobes and almost uniform sensitivity in the frequency range of 0.2 MHz–15 MHz (with variations less than 5 dB). Measurements performed with the PVDF transducer were used to estimate the sensitivity of the fiber-optical Sagnac interferometer.

composite structure. There are 18 maxima directly corresponding to the 19 layers of this sample.

Although subtle, the differences between these two signals are significant. First, the back-wall signal is bipolar (negative-positive) for the PVDF transducer and tripolar (negative-positive-negative) for the Sagnac interferometer. The PVDF response is only bipolar because the front surface of the sample is immersed in deionized water to produce a water/composite interface that launches a nearly unipolar OA pulse.¹⁰ In contrast for the non-contact, all-optical system, the probe OA pulse is bipolar due to the reflection from the air/composite interface.¹⁰

The second significant difference is that structure reflections are smaller for the PVDF transducer than for the optical detector. Since the PVDF transducer averages over its aperture (6 mm), reflections from heterogeneities are decreased but signals from flat interfaces are increased compared to the point-like optical detector. This is clearly seen in Fig. 6(b) where the signal is recorded near a thin brass foil inclusion in the composite structure. The “defect” signal has larger amplitude for PVDF detection.

B. Deconvolution with the reference signal

The reference signal illustrated in Fig. 4(a) by the red curve was obtained from an optically flat surface and can be used directly for high resolution imaging without any additional signal processing. An inhomogeneous and rough

surface, however, does not produce a stable low frequency signal because of thermal lens effects. This component is removed for signals recorded from composite samples by a HP filter prior to amplification and digitization to take full advantage of the dynamic range of the ADC (14 bit). To recover the full resolving power of the optical detector, a deconvolution procedure can be applied to recorded A-scan signals to approach the “ideal” unipolar temporal profile as much as possible.

First, we assume that the ideal response of the signal recorded from the composite samples is well characterized by the impulse response recorded with the ink covered PMMA plate. This is a reasonable assumption since the light absorption coefficient of the composite samples under study is more than 200 cm^{-1} , which gives a spatial scale of heat release in depth of about $50\text{ }\mu\text{m}$. Taking into account the sound speed in the composite of about 3000 m/s , we estimate that the spatial scale corresponding to US signal propagation during the laser pulse duration of 60 ns is about $180\text{ }\mu\text{m}$. Thus, the profile of the laser-generated US signal is mostly determined by the laser pulse envelope. Differences in light absorption coefficients and Gruneisen parameters of PMMA and composite materials modulate PA signal amplitudes, but not signal profiles.

Second, we assume that HP filtering by the Panametrics amplifier affects the Sagnac impulse response and the composite OA signal in precisely the same way. This means that for all frequencies outside the band of the very low

FIG. 6. Single shot (without signal averaging) A-line signals recorded with Sagnac (red line) and with contact PVDF (blue line) detectors in the region without (a) and with (b) inclusion (brass foil). A 20 mm deep tank filled with deionized water was attached to the sample front surface to acoustically couple the PVDF transducer. All other experimental conditions were identical for both methods. All 19 layers of the composite sample are evident, as well as the inclusion which generates multiple reverberations.

frequency (below a few hundred kHz) instabilities of the composite OA signal, the only difference in its profile compared with the reference is due to scattering by sample heterogeneities. Thus, inverse filtration (or deconvolution) of the A-scan recorded for the composite sample with the reference OA signal can be represented in the frequency domain as

$$S_{processed}(f) = \frac{S_{HP}(f)}{S_{Ref}(f)} * Filter(f). \quad (3)$$

In Eq. (3), $S_{processed}(f)$ is the spectrum of the resulting deconvolved signal, $S_{HP}(f)$ is the spectrum of the recorded A-scan after analog HP filtering with the Panametrics amplifier, and $S_{Ref}(f)$ is the spectrum of the OA reference signal from the PMMA plate. $Filter(f)$ is the spectrum of a bandpass filter designed to remove unwanted very low and very high frequencies. For the results presented below, this filter is defined as

$$Filter(f) = (1 - \exp(-(f/f_0)^2) * \exp(-(f/f_1)^2 - (f/f_2)^4)), \quad (4)$$

where $f_0 = 100$ kHz, $f_1 = 11$ MHz, $f_2/f_1 = 1.2$. The resulting processed signal is produced by inverse Fourier transformation of $S_{processed}(f)$. The result of this processing for the signal of Fig. 6(a) is presented in Fig. 7.

FIG. 7. A-scan signal detected with Sagnac Interferometer (red line—note that this is identical to the red tracing in Fig. 6(a) and the signal after deconvolution (black line).

C. B-scan images

Figure 8 illustrates B-scan images obtained within the defect region of the sample. Each B-scan consists of 450 A-scans (RF signal – bipolar display), normalized by their amplitudes at the front surface. Normalization was needed because the light absorption coefficient of the composite

FIG. 8. Typical B-scan images obtained with Sagnac (a)—for single-shot regime and (b)—after application of 10 moving averages, and PVDF (c) detectors. PVDF detection demonstrates 20 dB better signal to noise ratio in comparison with Sagnac single shot regime but the layered structure is better seen with the point-like ($7.5 \mu\text{m}$ focal spot diameter) optical detector due to no signal averaging over the transducer aperture.

sample, local sample roughness, and small displacements of the Sagnac focal point from the sample surface can change from point to point. All of these factors influence only the measured signal amplitude, however, and do not appreciably change its profile.

The sample was moved at a constant speed of 1 mm/s over a distance of 30 mm in the lateral direction, corresponding to a $66\text{ }\mu\text{m}$ spacing between A-scans. The laser pulse repetition rate was 15 Hz, but could be increased to 1 kHz keeping the same sample translation speed, and ultimately to 76 kHz for applications requiring very fast translation. Single shot (i.e., one laser firing creates one A-line) images obtained with Sagnac and PVDF detectors are presented in Figs. 8(a) and 8(c), respectively, whereas the Sagnac based B-scan resulting from a moving average of 10 adjacent A-scans (i.e., $660\text{ }\mu\text{m}$ averaging window) is illustrated in Fig. 8(b).

All images clearly present the inclusion in the composite structure. As noted above (see Fig. 8), Sagnac-based images show the layered composite structure more clearly than the PVDF-based one. The reason is that the Sagnac detector is point-like—the probe optical beam diameter at the focal point is only $7.5\text{ }\mu\text{m}$ in diameter, much smaller than the acoustic wavelength. Thus, there is no averaging over the detector aperture. For PVDF detection, the signal was averaged over the 6 mm transducer aperture, which emphasizes signal reflections from large flat heterogeneities placed perpendicular to the propagating beam direction where signal components from different defect points propagate to the detector surface in-phase. The opposite effect—reduction of signal amplitude—occurs when signals come from small irregularities or from tilted and non-flat (within the transducer aperture) inclusions.

It is quite evident from Fig. 8 that the B-scan image obtained with Sagnac detection is noisier than that obtained with the wide-band PVDF transducer. This is entirely expected given the dimensional differences in the two detectors (i.e., 6 mm versus $7.5\text{ }\mu\text{m}$). In addition, the pump laser produces a larger incident pressure pulse for the case of the PVDF transducer because of the water/composite interface.^{10,13,47,48} Indeed, heating the thin water layer adjacent to the composite surface produces an additional OA source. In auxiliary experiments (not shown in this paper), we launched the OA pulse on one side of a sample and detected it on the other side of the sample using the PVDF transducer (forward detection mode,^{9,10,47,49}) and observed that water coupling produced an OA signal twice as large as that for air coupling.

As will be discussed in detail below, the PVDF transducer is about one order of magnitude more sensitive than the Sagnac detector. Surprisingly, the difference is just one order of magnitude, not three or four orders as is usually the case for optical detectors capturing light from a composite material surface with an effective reflectivity less than 1%. As is evident from Fig. 8, the sensitivity of the Sagnac detector is sufficient for non-contact imaging of the composite materials used in this study even in a single shot regime. Furthermore, since the pump fiber laser can fire at a very high repetition rate (76 kHz for the current laser), scanning

can be performed very quickly while additional signal averaging can be applied to recorded RF signals. Because the lateral resolution generally cannot be better than the pump laser beam diameter, 1.5 mm in our case, and the scanning step is only $66\text{ }\mu\text{m}$, a simple moving average filter can be applied in the translation direction. Such processing does not degrade lateral resolution if the averaging region is smaller than $750\text{ }\mu\text{m}$ (half of the laser beam diameter). As seen in Fig. 8(b), the noise is greatly (by a factor of $\sqrt{10}$, SNR gain of 10 dB) reduced with this simple processing and the resulting image is of comparable “visual quality” to the PVDF images. Note that moving average filtering can also be applied in two dimensions for three-dimensional data acquisition.

Figure 9 illustrates the dependence of the image amplitude along the lateral (X) direction through the brass inclusion, as shown in the right corner of the figure. This plot can help evaluate the lateral resolution of the detection system. For both PVDF and Sagnac schemes, the slope width corresponds very well to the pump laser beam diameter of 1.5 mm. This is not a surprising result because the inclusion is located in the near field—1.5 mm from the surface. If the defect is located deeper, spatial averaging over the transducer aperture plays the main role in defining lateral resolution.

D. Sensitivity of Sagnac detector

To determine the sensitivity of the Sagnac detector, the most important characteristic of a detection system, we directly compared the Sagnac detector’s noise limit to that of the calibrated PVDF transducer. Using the measured noise equivalent pressure (NEP) of the PVDF transducer of 10 Pa, and a comparison of the signal to noise ratio of the two detectors over the same frequency band, the NEP for the overall Sagnac detection system is estimated to be 400 Pa. Although significantly higher than that of the PVDF transducer, this NEP is quite remarkable given that the detection aperture of the Sagnac is only $7.5\text{ }\mu\text{m}$ in diameter. To judge

FIG. 9. Cross-sections of B-scan images along the X-axis in a defect region, as shown in the enlarged pictures in the upper right corner. The blue curve corresponds to the PVDF transducer and the red one to the Sagnac detector. Both detectors exhibit 1.5 mm lateral resolution corresponding to the pump laser beam diameter.

its absolute performance, the Sagnac should be compared to an “ideal” acoustic detector of the same bandwidth and area.

The ultimate limit for any acoustic detector is set by the Johnson–Nyquist noise associated with molecular thermal vibrations, as given by the well-known formula

$$W_{Nyquist} = 4k_B T \Delta f = 8.6 * 10^{-14} \text{ W}, \quad (5)$$

where k_B is the Boltzmann constant, $T = 300 \text{ K}$ and $\Delta f = 5.2 \text{ MHz}$ correspond to the measured reference signal spectrum.

On the other hand, the acoustic noise power based on a NEP of 400 Pa measured for the Sagnac detector can be easily estimated as

$$W_{Sagnac} = \frac{P_{Noise}^2}{z} S_{focal} \cong 1.5 * 10^{-12} \text{ W}. \quad (6)$$

Here, $z = \rho c$ is the acoustic impedance of the composite ($\rho = 1.5 * 10^3 \text{ kg/m}^3$, $c = 3000 \text{ m/s}$), $S_{focal} = \pi d^4/4$ is the Sagnac focal area, and $d = 7.5 \mu\text{m}$ is the beam diameter.

Thus, the noise power of the Sagnac detector is only 17 times that of an ideal acoustic detector of the same size and bandwidth, representing a detector system noise figure of 12.3 dB. This figure overestimates the noise factor of the interferometer itself since it includes all of the electronics in the signal path. As discussed below, this performance can be improved in future designs. Nevertheless, a 12.3 dB system noise figure for optical detection from rough composite surfaces reflecting less than 1% of incident light over a $7.5 \mu\text{m}$ diameter detection aperture should enable non-contact LU inspection systems with exquisite sensitivity and spatial resolution.

IV. DISCUSSION

Optical interferometers have been used extensively for non-contact, optical detection of ultrasound. Most designs require a reference arm that complicates the system and requires complex stabilization methods. The Sagnac approach presented here overcomes most of the limitations of previous designs because both interfering beams come from the sample surface and no reference arm is required. In addition, the low coherence SLD employed as the optical probe dramatically reduces the effects of parasitic interferences within the interferometer itself.

The interferometer presented here is assembled from fiber-optic components and includes a balanced detection scheme to improve sensitivity. Most components are custom designed and leverage the most recent advances in optical sources and fiber-optic components developed for the optical communications industry. This was the reason that the standard optical communications wavelength of 1550 nm was used. Most of the optical fibers in our interferometer are PM. This feature enables a very flexible design that can be easily installed.

Although the noise figure of the Sagnac detector is quite small, the overall NEP of the detection system is modest because of the small detection area. For a mirror-like sample surface, the probe beam diameter can be increased and the

overall optical power increased to dramatically reduce the NEP. However, the main problem with LU inspection of composite samples is that the sample surface is quite rough, which requires a focused probe beam and high NA optics to efficiently collect backscattered light. In future studies, we will explore different focal depth objectives with higher power light sources to optimally collect backscattered light from composite samples with different surface roughness.

The Sagnac detector was integrated into a LU system that also employed a different approach for the pump laser. Instead of a high pulse energy, low repetition rate source, we used a low pulse energy, high repetition rate laser focused to a relatively small spot size (1.5 mm in diameter) to produce an acoustic source of sufficient strength for many applications in composite NDT&E. The high repetition rate can compensate for the small spot size, potentially enabling very fast scan speeds for many applications. In particular, single shot images of the composite sample studied here are of sufficient quality to enable operation of the LU system at very fast scan rates using the maximum 76 kHz pulse repetition rate of the pump laser. Such a system represents a cost-effective approach to NDT&E of composites with a performance level very difficult to duplicate using conventional LU systems.

Given the broad bandwidth, high spatial resolution, and overall sensitivity of the LU system presented here, we plan to use it to develop advanced signal processing methods extracting important materials properties that can better characterize composite components. For example, the broad bandwidth of the present system can potentially be exploited for non-destructive imaging of material porosity. Future studies will focus on such applications.

Finally, the methods developed here for non-contact detection of bulk acoustic waves can potentially be extended to non-contact detection of surface acoustic waves (SAW). A sensitive, point-like, non-contact SAW detector would be very useful in diagnostics of material surface and subsurface layers and also in residual stress evaluation. The necessary theoretical background has already been developed and extensive experimental studies showing the success of SAW methods have been reported.^{50–56} Nevertheless, application of a very sensitive, non-contact, point-like detector could be very promising for field applications of these techniques.

V. CONCLUSIONS

A non-contact, all-optical, compact, inexpensive LU system for NDT&E of composite materials has been developed and demonstrated. It uses a compact fiber laser to launch an US probe pulse at the composite surface at repetition rates up to 76 kHz. The key component of the system, however, is a modified Sagnac-based fiber-optical balanced interferometer, which exhibited very good sensitivity in ultra wide-band US signal detection—noise equivalent pressure is about 400 Pa in the frequency band of 1–10 MHz for US signal detection from rough composite surfaces. To our knowledge, this is the best reported sensitivity for a non-contact ultrasonic detector of this dimension.

The fiber interferometer design is also quite robust for practical applications—it does not require a reference arm;

detects acoustic pressure instead of displacement; does not need adjustment and stabilization; and can be mounted on any surface. Note that this approach was enabled by recent developments in fiber-optic devices and components. It is also quite insensitive to parasitic interferences within the interferometer itself because a short $\sim 40\ \mu\text{m}$ coherence length SLD is used as the optical source.

Finally, the overall performance of the all-optical system has been demonstrated and compared for NDT&E applications with an equivalent system using contact wide-band detection. High resolution images of both the inherent composite structure as well as a well-defined inclusion within the sample clearly showed the capabilities of the system.

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