

**Fiber-Based Laser Doppler Velocimeter State of the
Technology for Verification and Validation of
Surface Velocity Measurements**

by Mark A. Mentzer

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1. Introduction

1.1 Motivation

The issue addressed is the lack of a means to measure surface deformation velocities to validate digital image correlation (DIC). The objective is to design and build a fiber-optic velocimeter or vibrometer based on homodyne detection, with single probe, fast Fourier transform (FFT) optimization, for curved surface deformation analysis.

This effort will provide the ability to characterize curved surface velocity range and maxima. It also affords the opportunity to place the probe inside clay or gel backing material to measure backface deformation (BFD). The fiber sensor probe can be used in a sacrificial manner in explosive events to characterize surface velocity up to the time the probe is destroyed, providing a low-cost alternative to x-ray and high-speed camera systems for measuring material velocities.

Multiple-channel, fiber-based laser Doppler velocimeters can be used in a variety of measurements, many of which involve velocities or displacements that may prohibit the use of commercial vibrometers. The initial application at the U.S. Army Research Laboratory Survivability/Lethality Analysis Directorate (ARL/SLAD) is for verification and validation of measurements acquired with DIC for ballistic event characterization. Typical applications involve velocities on the order of 1000 m/s and displacements on the order of 10 cm. Commercial vibrometers are not suitable for these conditions but the parameters are well within the capability of velocimeters (1).

For instance, we wish to characterize clay deformation events behind body armor. The primary approach to characterizing the deformation is to use x-ray cineradiography to look through the clay to the deformation itself. The approach is complicated by the attenuation of the clay and lack of fast decay scintillators for high-speed acquisition. As SLAD advances the x-ray capability, a parallel approach to measurement is desired for validation and verification, such as the developmental magnetic resonance imaging (MRI) coplanar cineradiography (CCINE) system recently developed by SLAD's Mark Mentzer and James Gurganus (2). A fiber-based laser Doppler velocimeter generates complementary data with the laser directed at either the backface of the clay block or the rear of the body armor through a small hole in the backface and clay.

1.2 Operational Concept

The velocimeter is based on heterodyne mixing of two portions of the beam from a laser, one portion of which has been Doppler-shifted during reflection from a moving surface (3–5). In this case, the beams are confined to a fiber except during launch toward the moving surface and the return trip to a collimator. While the 1550-nm beams induce only direct current output from the

receiver (due to the terahertz frequencies that are outside the receiver bandwidth), the beat frequency of the mixed beams is low enough to be followed by a high-speed optical detector. The beat frequency contains information about the velocity of the reflecting surface, which in turn is used to deduce position information.

For example, a laser emitting 1554.54 nm has an associated frequency of 192.850 THz. The same beam, when reflected from a surface moving at 500 m/s, will be Doppler-shifted to induce a beat frequency of 645 MHz. The beat frequency is linear with the velocity of the reflecting surface, i.e., a surface moving at 250 m/s will induce a beat frequency of 323 MHz.

Two optical receiver configurations were characterized by Mentzer (6) in the fall of 2010. One (Newport AD-200ir) had a bandwidth of 2.5 GHz and a sensitivity of -24 dBm at 1550 nm. This sensitivity is known to be adequate for systems with a relatively high-power laser (500 mW). The second detector (LT S155001A0) had a lower bandwidth of 650 MHz but with ~ 500 times higher optical sensitivity. The more sensitive detector was evaluated to explore the possibility of using a lower-power, reduced-class laser.

1.2.1 System Configuration

The layout of the prototype velocimeter is shown in figure 1. One of three 1550-nm lasers was used, depending on the information desired: (1) HP 81689A 5-mW tunable laser; (2) Amonics ADFB-1550-10-B-CW-FA 10-mW fixed frequency laser; or (3) IPG Photonics ELR-2-1550-LP-SF 2-W fixed frequency laser. The 95/5 splitters were both Oplink SWFC1055LU01. The circulator was an AC Photonics PIOC315A2111 and the variable optical attenuator, part number OFC-MVOA-001, was purchased through Lightwavestore.com. The collimator/probe was an AC Photonics 1CL15A300LCC01. As previously mentioned, two optical detectors were characterized: the Newport AD200ir and the LT S155001A0. The oscilloscope was a 1-GHz, 20-GSa/s Agilent DSO9104A.

1.2.2 Design Considerations

1.2.2.1 Oscilloscope Bandwidth and Sample Rate

The oscilloscope must have sufficient bandwidth to see the beat frequency, which scales linearly with the velocity of the target. The maximum anticipated velocity for this application was 500 m/s, which corresponds to a beat frequency of 645 MHz. In order to faithfully reconstruct the beat frequency, the oscilloscope must sample at a frequency at least twice that of the beat frequency. The 20-GSa/s oscilloscope easily satisfies this criterion and can be set to lower sample rates depending on the anticipated target velocity.

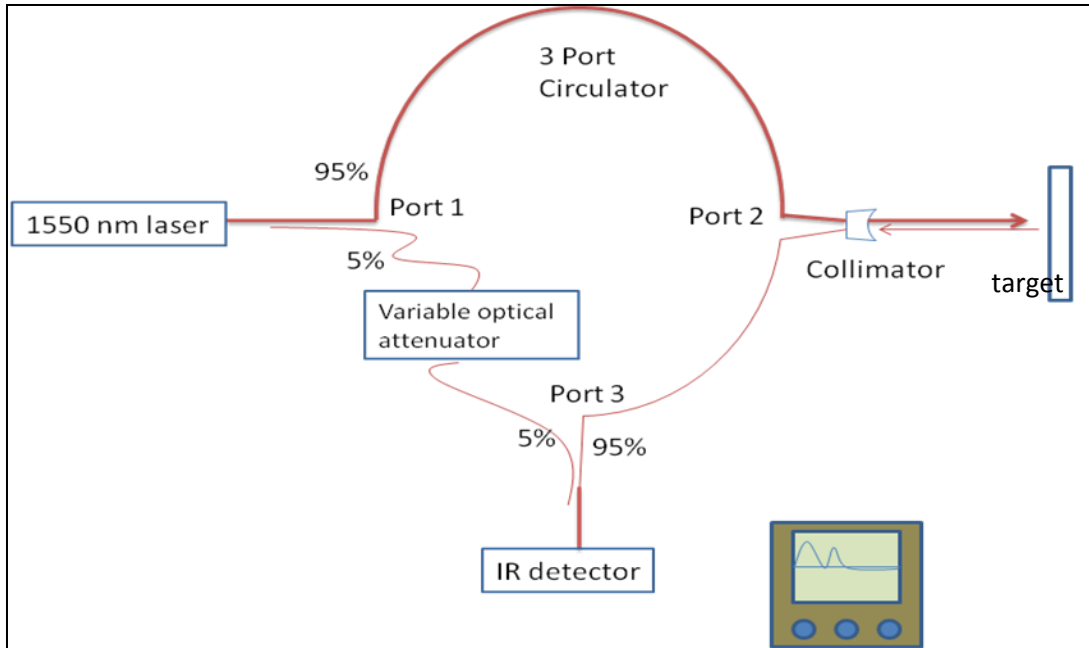


Figure 1. Velocimeter layout.

1.2.2.2 Laser Power

There are two considerations when choosing a laser: the optical detector sensitivity and the safety regulations associated with the laser classification. The details of the detector evaluations will be given later in this report. In short, the Newport AD-200ir worked well with 100 mW of launched 1554-nm light and the LT S155001A0 detector was about 500 times more sensitive (i.e., it is anticipated that a 5-mW laser would be more than adequate).

For a fiber-coupled 1550-nm laser that exits the fiber without being focused, the classifications are: <10 mW is class 1, 50–500 mW is class 3a, 500 mW–1 W is class 3b, and >1 W is class 4. (5) Note that a collimator was used in this system.

1.2.2.3 Access to Variable Attenuation in the Nonshifted Path

A wide dynamic range variable optical attenuator was used in the leg of the optical circuit that was not Doppler-shifted. The intent was originally to mix roughly equal amounts of Doppler-shifted and non-Doppler-shifted light by tuning the attenuator to roughly mimic the return loss of the collimator. It was found, however, that higher light levels in the nonshifted path increased the available signal.

1.2.2.4 Choice of Detector

The two detector parameters of interest are sensitivity and bandwidth. As was mentioned previously, a bandwidth of 645 MHz will be useful for speeds up to 500 m/s. The LT S155001A0 detector had a bandwidth of 650 MHz. The Newport AD-200ir detector had a bandwidth of 2.5 GHz, corresponding to a maximum velocity of 1938 m/s.

The Newport detector is specified to have a sensitivity of -24 dBm without reference to the exact criteria against which it could be characterized. Based on the relative voltage at a fixed input optical power, the LT S155001A0 detector's sensitivity was measured to be about 500 times greater than that of the Newport device. Note that these two detectors were utilized for the evaluation based on their availability at the time of the experiments. They do not necessarily represent the full range of options or the optimal price points for the trade space of interest.

2. Results

2.1 Detector Sensitivity and Frequency Response

An HP 81689A tunable laser set to 1554 nm was used to characterize the sensitivity of the detectors. The output optical power was measured with an HP 81536A power meter, after which the power was coupled into the detectors. The electrical output from the detectors went to a 50-ohm input on the Agilent DSO9104A oscilloscope. In this mode, the Newport detector gave an output with a signal-to-noise >1.0 for optical inputs down to -30 dBm (1–2 mV on the oscilloscope). The LT detector still produced 10–20 mV on the oscilloscope at -70 dBm but transitioned to photon counting mode; lower light levels would produce only fewer pulses with the same amplitude. The gain control voltage for the LT device was set to 0.95 V, but the device produced visible pulses on the oscilloscope with the gain control set to 0.8 V as well. The 500 times sensitivity comparison made previously is based on a comparison of the relative current outputs of the detectors at a fixed light level.

No high-velocity testing was carried out with either detector; rather, only proof-of-concept traces were generated by translating a card in the path of the laser. While the ability of the detectors to characterize high velocities was not verified, there is no reason to doubt they would perform consistent with their respective bandwidths. It should be noted that the LT detector is sensitive to polarization. When the LT device was used, a ThorLabs FPC560 polarization controller was placed in the optical circuit just prior to the detector.

2.2 Collimator Return Loss

The amount of light coupled back into the collimator would be down by about 40 dB relative to the amount launched (figure 2). Obviously, the ability to capture the reflected light strongly impacts the power requirement for the 1550-nm source laser. The collimator was purchased

from AC Photonics (part number 1CL15A300LCC01). It had a 300-mm working distance. An HP 81536A power meter was used to measure the amount of light launched into port 1 of the circulator and the amount present at port 3 following the collimator. The beam diameter appeared to be about 0.5 mm when viewed using an infrared sensing card.

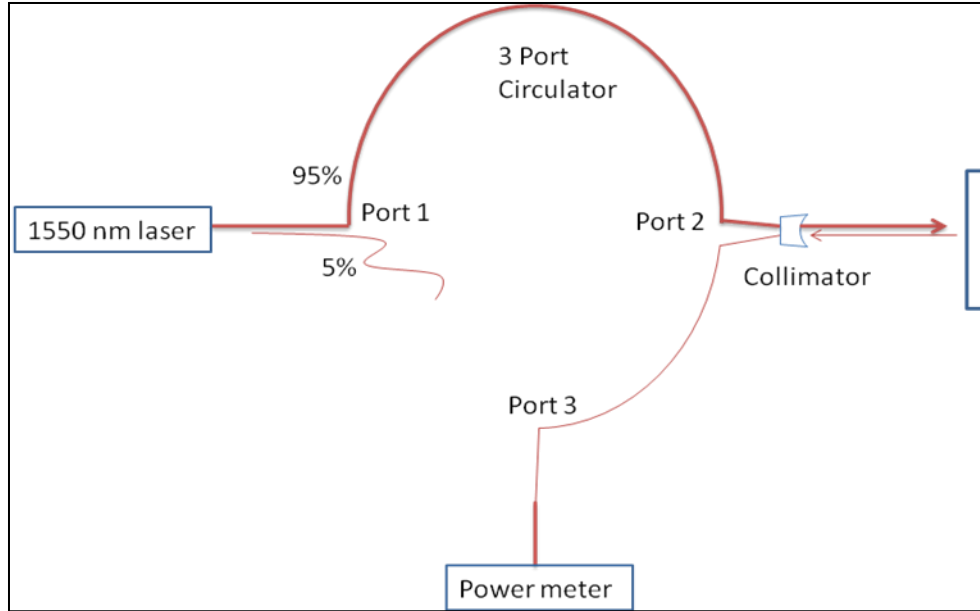


Figure 2. Configuration for measurement of collimator return loss.

Contrary to expectations, the return loss when the laser was reflected from a white note card at a distance of about 2 in was about -60 dB relative to the launched power. Consistent with the recoupled power of diffuse reflection, there was only about a 3-dB change in the return loss when the beam was aimed at a card 32 in away, a black wall, or plywood.

A larger beam collimator is suggested (7.0-mm beam diameter, ThorLabs part number F810APC-1550). In addition to illuminating a larger area, the beam from this collimator should be easier to recouple off of the moving surface.

3. Discussion

3.1 Commercially Available Velocimeter Alternative

A commercial integrated version of the fiber portion of the velocimeter is available from Third Millennium Engineering (www.tmeplano.com). Third Millenium offers multichannel systems with up to 20-GHz-PIN analog receivers and a visible spotting laser coupled into each probe. The detectors are similar in sensitivity to the Newport device described previously but perform adequately with the appropriate laser.

The Third Millennium system does not include a 1550-nm source laser since various system configurations require different laser power levels. Depending on the number of channels, an EDFA-amplified laser of a few watts output power may be an appropriate choice. (One example is the IPG Photonics ELR-2-1550-LP-SF.)

While the motivation for investigating the velocimeter system was the search for a low laser power operation for safety considerations, the extreme cost of the detector choices available for this approach seems to outweigh the marginal safety gain based on the class of the laser.

3.2 Path Forward

The results indicated that it would not be possible to use a 10-mW Amonics 1550-nm source with the Newport detector. In order to demonstrate that the Newport detector could be used with a more powerful laser, about 100 mW were launched from a 2-W IPG Photonics laser borrowed from ARL's Weapons and Materials Research Directorate. In this case, it was easy to get an oscilloscope trace by waving a card in the beam path.

The analysis could be as simple as a Fourier transform of the oscilloscope trace, which would give the beat frequency content and the corresponding velocity range of the moving surface. A more sophisticated approach is to use a moving window for the transform; this gives the velocity as a function of time during the event. In principle, the maximum displacement of the surface can be obtained by integration of the velocity profile.

A high-pass filter is recommended at the oscilloscope input to avoid spurious triggering from vibrations of no interest. The cutoff frequency for the filter would be chosen based on the minimum velocity of interest (a 1-MHz cutoff would correspond roughly to 1 m/s). As previously mentioned, the 7-mm beam diameter collimator is recommended for ease of coupling the return beam.

Based on experimentation to date, system design trades can now be affected to meet the typical requirements for such a system. Typical velocities and displacements necessitate a different detector than the LT device, while the safety benefits of a lower power laser would require a more sensitive detector. Analysis of alternatives must, therefore, be performed for a suitable detector.

3.3 Range Applications – CCINE Validation and Verification

Additional motivation for development of a velocimeter (aside from the DIC validations) is verification and validation of data from an x-ray cineradiography system. The particular data of interest were the time to maximum deformation and total event time for a shot on clay-backed body armor. The cineradiography system would be used to look through the clay as the body armor deformed into the clay and derive timing for the evolution of the event. Since the clay backface deformation timing can potentially be used to infer the armor deformation timing, a velocimeter beam on the plywood backface could be used to verify the CCINE data.

A second verification approach would be to create a small channel through the plywood backface and clay to the rear of the armor. On the assumption that the small channel would have a negligible effect on the event, the laser beam could be directed at the actual armor to measure event timing. In this case, information on the velocity and position of the armor during deformation would obtain in addition to the timing information.

4. Conclusions

The design trades and preliminary tests described herein provide adequate justification for the pursuit of a velocimeter/vibrometer system for DIC and CCINE validation. Additional design trades are being performed to identify the optimum system parameters pursuant to these applications. SLAD would benefit greatly from the addition of such a system to its experimental suite and ballistic measurement methodology. Continued investigation into the best approach continues, in anticipation of CCINE applications and continued progress in DIC techniques, for a variety of ARL test range applications.

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