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Weapons Program Technical Report

Laser Wavelength Shift from Splitters and Switches

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REVISION LOG

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Q-6-TR-0101U	A	Initial Release

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LIST OF ACRONYMS

FFT	Fast Fourier Transform
HE	High Explosive
LANL	Los Alamos National Laboratory
M&TE	Measurement and Test Equipment
N/A	Not Applicable
NIST	National Institute of Standards and Technology
PDV	Photon Doppler Velocimetry
Q-6	Detonation Science and Technology Group
RF	Radio Frequency
S&CL	Standards and Calibration Laboratory
TA	Technical Area
TS&I	Traverse Solutions and Instrumentation, LLC
VOA	Variable Optical Attenuator
WL	Wavelength

1.0 PURPOSE

The Detonation Science and Technology Group (Q-6) operates several photon Doppler velocimetry (PDV) systems as a diagnostic tool for measuring velocities in the 1–10 km/s range during high explosive (HE) detonation experiments. Q-6 uses "heterodyne" PDV systems that are produced by Traverse Solutions and Instrumentation, LLC (TS&I). These heterodyne systems combine wavelength (WL) tunable source and "reference" lasers with a WL offset of 10–100 pm from each other.[1] Properly setting the source and reference WLs for an experiment can be critical for collecting the desired experimental data.

The tunable lasers report WL readings in their control software, but these readings are based on a lookup table from a temperature reading and are not able to be calibrated. Therefore, recent test fire programs that require PDV as a diagnostic have also implemented requirements for monitoring the WL of the tunable lasers using a precision WL meter. To monitor the WL of several PDV lasers without disconnecting any patch fibers form the experimental setup, Q-6 developed a system splitters with a coupling ratio (%) of 99:1 and an optical switch with the switch output going to a single WL meter. A brief experiment was developed to determine if the splitters and/or switch introduced any WL bias into the readings. The purpose of this report is to document the system, the experiment, and its results.

2.0 BACKGROUND

In its most basic form, PDV is a fiber laser interferometer where the Doppler frequency shift caused by a moving object is mixed with the base laser frequency to create a beat frequency that corresponds to the velocity of the object.[2] The beat frequency is

$$B = \frac{2}{\lambda_0}|u| \ , \qquad (1)$$

where λ_0 is the base laser frequency and u is the velocity of the object. The beat signal is digitized on an oscilloscope and then processed through a Fourier transform so that the corresponding beat frequency, and therefore velocity, of the moving object can be calculated. The basic hardware is shown in Figure 1.

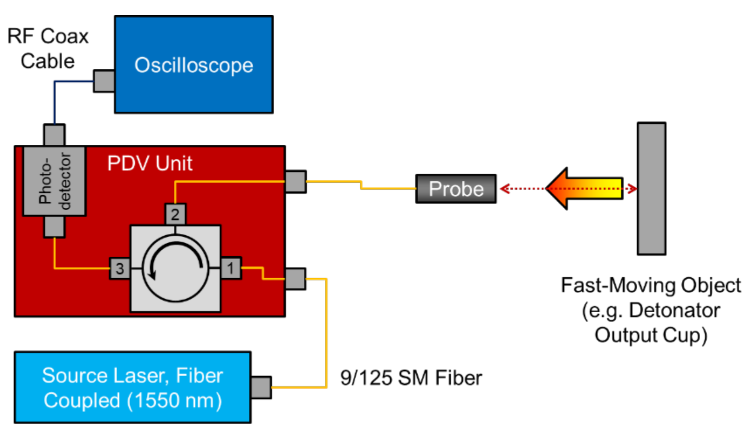

Figure 1. Basic PDV system.

Light from the source laser enters a fiber circulator at Port 1 and exits at Port 2, where it is delivered to the moving object using a "probe," which is typically a pigtail collimating or focusing lens. The moving object reflects light back into the probe, where it mixes with some of the source light reflected at the probe and travels into circulator Port 2, which directs it to exit at Port 3. The mixed light at Port 3 is sent to a photodetector where it is converted from an optical signal to an electrical radio frequency (RF) signal and captured on a high-bandwidth (multi-gigahertz) digitizing oscilloscope. In typical applications of PDV for HE experiments, a laser centered at a WL of 1550 nm and optical fibers/components (circulators, detectors, etc.) for single-mode 1550-nm light are used because of their ubiquity in telecommunication applications. At 1550 nm, 1.29 GHz of oscilloscope bandwidth is required for each kilometer per second of velocity measured, according to Equation (1).

More advanced PDV systems add enhancements such as variable optical attenuators (VOAs), power meters, feedback control, and multiple PDV channels in a single chassis. They may also add the option to input a second "reference" laser that is mixed with the probe output (i.e., between circulator Port 3 and the detector in Figure 1) using an optical combiner to create a "heterodyne" or "upshifted" PDV system that has a base non-zero beat frequency at zero velocity. The PDV systems used at Q-6 are modular chassis systems built by TS&I that incorporate all of the above features.[3] A schematic of the TS&I system is shown in Figure 2.

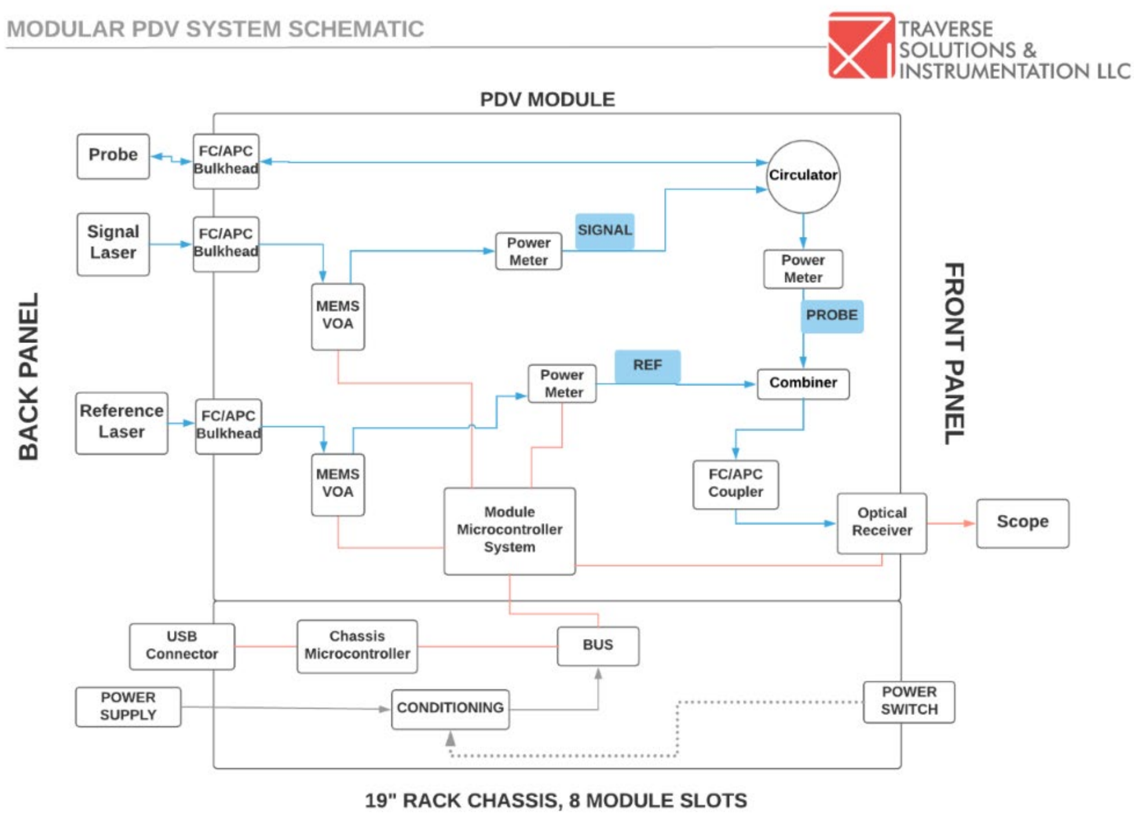

Figure 2. Heterodyne PDV block diagram as implemented in Q-6's hardware manufactured by TS&I.[3] Courtesy of TS&I, LLC. Schematic copyright 2019 TS&I, LLC; all rights reserved.

Heterodyne PDV is desirable for measuring transient velocities that change very quickly, such as those in explosively driven flyers. As an example, consider a goal of capturing a velocity change of 0.5 km/s sampled at 50 GS/s (20 ps/pt) with a desired velocity-time history interval of nominally 5 ns [256-point fast Fourier transform (FFT) window] to capture all of the desired behavior. The 0.5-km/s velocity has a beat frequency of 645.2 MHz (Equation 1). In the 5-ns window, there will be, at most, 3.2 wave cycles in the FFT window. If the window covers an initial rise from zero signal to up to 645.2 MHz partway through the window, then there are fewer cycles, making it difficult to measure the velocity. However, if the zero velocity signal is upshifted to 2 km/s, then the 0.5-km/s shift shows up at 2.5 km/s or 3.23 GHz. In this case, there are 16 wave cycles in the FFT window, making it much easier to find the velocity change.

A drawback to the heterodyne PDV system design in use at Q-6 is that it does not completely remove the homodyne beat signal from the digitized signal. Thus, a weaker velocity signal is still present from zero to the maximum speed measured during the event of interest. If this signal crosses the heterodyne-shifted signal, then analysis of the data may become complicated. It is therefore critical to choose the heterodyne velocity shift appropriately.

The WL of light is related to its frequency by

$$c = \lambda\nu \ , \tag{2}$$

where c is the speed of light in a vacuum (2.998×10^8 m/s) and ν is frequency. To determine the effect of a change in frequency, we take the derivative

$$\frac{d\lambda}{d\nu} = -\frac{c}{\nu^2}, \tag{3}$$

which, for a small shift in WL, approximates to

$$\Delta\lambda = -\frac{c}{\nu^2}\Delta\nu \ , \tag{4}$$

where $\Delta\lambda$ is the WL shift required. We can substitute Equation (2) into Equation (4) for the base WL such that

$$\Delta\lambda = -\frac{c}{(c/\lambda)^2}\Delta\nu \ , \tag{5}$$

allowing us to quickly calculate the approximate WL shift required to achieve a given offset frequency. From Equations (1) and (5), it follows that each kilometer per second shift (1.29 GHz) requires a WL shift of 10.34 pm (0.01034 nm) from the base 1550-nm WL. Hence, it is critical to have precise control and measurement of the base and reference laser WLs when setting up a heterodyne PDV experiment.

The reference laser upshift is accomplished in Q-6 PDV systems using tunable NKT Photonics BASIK E15 erbium-doped fiber lasers that are thermally tunable over a range of ±350 pm.[4] These lasers are adjusted by setting the desired WL shift in their control software. The same software reports the actual laser WL in real time. To the best of Q-6's knowledge, the NKT hardware and software monitor the temperature at some position in the laser and use a lookup table to report the WL. In real-world applications, the reported WLs have been found to not align with the actual velocity upshift seen in HE tests. For example, a requested and reported shift on the reference laser of 60 pm in one PDV system resulted in a zero velocity upshift of 3.8 km/s after FFT processing, which corresponds to an actual upshift of approximately 40 pm. Therefore, an in-situ method of measuring the actual laser WL is desirable and has been implemented as a requirement for certain test programs.

3.0 POWER PICKOFF METHOD

At Technical Area (TA)-40, Chamber 15, one of Q-6's TS&I PDV systems has been modified for remote, in-situ measurement of laser WL from all of its source lasers (four channels and reference) using a "power pickoff" method with 99:1 ratio optical splitters. A schematic of the setup is shown in Figure 3. Each NKT BASIK module is connected to the input port of a Thorlabs TN1550R1A1 1550-nm single-mode narrowband (±15 nm) 99:1 coupling ratio fused fiber-optic coupler used as a splitter. The 99% output ports are routed either to the signal ports on the TS&I chassis (where they are then passed through a VOA, the circulator, and on to the probe port) or, for the shifted WL reference laser source, to a Newport 4x1 fused splitter where 25% power is passed to each TS&I reference input port.

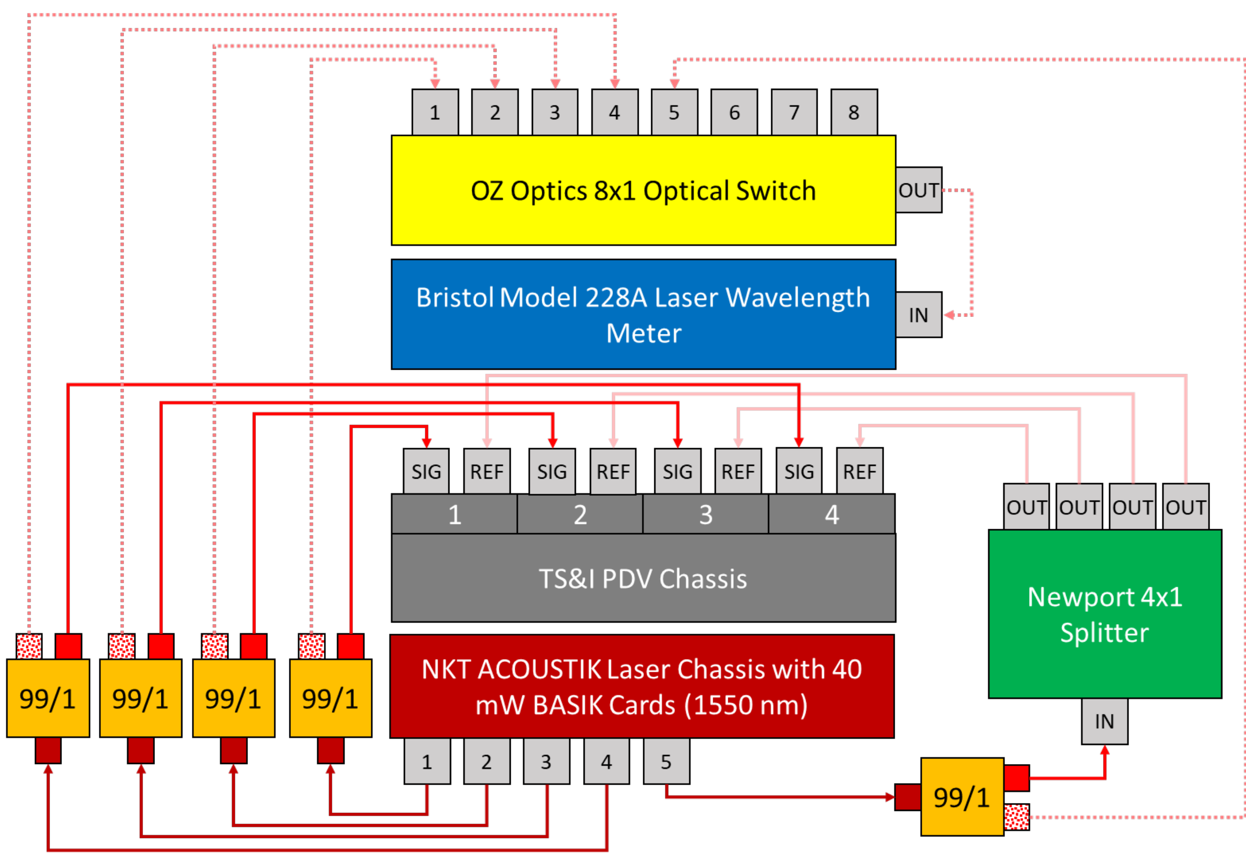

Figure 3. Schematic of TS&I PDV system with NKT BASIK tunable source lasers modified for in-situ laser WL measurement.

The 1% splitter outputs (the "tap" or "pickoff" ports) are connected with single-mode fiber (Corning SMF-28) patch cables to an OZ Optics FOS-1000-1-1x8-3A-1250/1650-9/125-S 8-port fiber switch with digital control. The output of the switch is connected to the input port of a Bristol 228A laser WL meter. The 228A has a claimed measurement accuracy of 0.3 pm (0.0003 nm) at 1550 nm, a repeatability of 0.1 pm (0.0001 nm), and a display resolution of 0.00001 nm. The 228A currently in use at Chamber 15 was calibrated by Bristol at their factory. This unit has not been through an accredited calibration under Los Alamos National Laboratory's (LANL's) Standards and Calibration Laboratory (S&CL) measurement and test equipment (M&TE) program because the only available calibration vendor [the National Institute of Standards and Technology (NIST)] requires 6 months to calibrate a laser WL meter at the time this report is being written. Q-6 has shipped two additional Bristol 228A meters to NIST for calibration but determined that it was acceptable to begin work with a factory-calibrated 228A while waiting for those units to return.

This combination of splitters, a switch, and a one-input power meter allows for in-situ measurements of the WL of all four signal lasers and the reference laser just before an HE experiment without the need to disconnect/reconnect any fibers. An additional benefit is that both the switch and the WL meter can be controlled/monitored remotely so that the WLs can be recorded from the control room just before charging the fireset to execute an HE experiment. However, it raises the possibility that the additional hardware (splitters, switch, and patches) may cause some shift (bias) in the recorded WLs compared to a direct connection from the laser source to the WL meter. Therefore, a brief experiment was designed to determine the amount, if any, of WL bias in the WL readings.

4.0 EXPERIMENTAL INVESTIGATION

Before testing for bias, the lasers were tested for changes in WL (stability) during warmup and power changes in the complete setup as shown in Figure 3. All five lasers had WL recorded at start and after a 30-min warmup at full output power (40 mW). One laser (the shifted reference laser, "Channel 5") was tested for changes in WL at power settings of 12 mW, 20 mW, 30 mW, and 40 mW. A brief stability test at 12 mW and 40 mW was also conducted. These tests were of interest because the Bristol 228A has a maximum input power of 30 mW, which is less than the NKT BASIK's maximum power output typically used as input to the TS&I PDV system. Finally, the WL was measured for all five lasers, with power set to 12 mW, directly to the Bristol (with an SMF-28 fiber patch cable with FC/APC connectors), with the splitter installed but the OZ Optics switch bypassed, and finally in the full laser-splitter-switch-meter configuration. In summary, the tests conducted included the following.

1. Cold/warmup test on all channels
2. Power sweep and stability on one channel
3. Splitter and switch bias on all channels

The Bristol 228A makes measurements at 10 Hz (0.1 s per measurement) and was set to average 32 samples per reading (3.2 s) for these experiments. Therefore, between each measurement, the meter was allowed to stabilize for 10 s or more before the reading was recorded.

5.0 TEST RESULTS

5.1 Cold/Warmup Test

These measurements were made with the 99:1 splitters and optical switch in place (see Table 1). "Cold" measurements were made right after turning on the laser. The laser power was set to 40 mW.

Table 1. Cold/Warmup Test Results.

Channel	WL (nm)		
	Cold	After 30 Min	Change
1	1550.11568	1550.11626	0.00058
2	1550.11563	1550.11588	0.00025
3	1550.11499	1550.11573	0.00074
4	1550.11740	1550.11743	0.00003
5 (Ref)	1550.15562	1550.15570	0.00008

5.2 Stability and Power Sweep

All measurements made on Channel 5 (Ref) were with the 99:1 splitter and optical switch in place (see Table 2). The stability test began with the laser being "cold" right after turning on. The power sweep was conducted after warmup and allowed for a few minutes to settle at each power level. Power readings are from the power meter in the Bristol 228A. The NKT software was reporting a WL of 1550.1698 nm. Results can be seen in Table 3.

Table 2. Stability Test Results (Channel 5, Splitter and Switch in Place).

Set Power (mW)	Time	WL (nm)	Power (µW)
12 mW (Maximum theoretical reading at Bristol 120 µW)	9:45 (Cold)	1550.15497	51.75
	9:47	1550.15500	51.76
	9:50	1550.15504	51.75
	9:55	1550.15511	51.74
	10:03	1550.15515	51.74
	10:10	1550.15518	51.74
	10:15	1550.15518	51.95
	10:20	1550.15518	51.95
	Maximum Change	0.00021	0.20
40 mW (Maximum theoretical reading at Bristol 400 µW)	10:20	1550.15583	177
	10:23	1550.15589	177
	10:25	1550.15584	177
	10:30	1550.15582	177
	Maximum Change	0.00007	0

Table 3. Power Sweep Test Results (Channel 5, Splitter and Switch in Place, NKT Software Reporting 1550.1698 nm).

Set Power (mW)	WL (nm)	Power (µW)
12	1550.15509	52
20	1550.15532	87.8
30	1550.15553	132
40	1550.15576	177
Change	0.00067	Not applicable (N/A)

5.3 SPLITTER AND SWITCH BIAS

Testing was performed after 30 min of laser warmup. The power set point was 12 mW. Table 4 lists the results of the splitter and switch bias testing.

Table 4. Splitter and Switch Bias Test Results.

Path	WL (nm)				
	Ch. 1	Ch. 2	Ch. 3	Ch. 4	Ch. 5 (Ref)
Source to meter direct (with patch cable)	1550.11568	1550.11532	1550.11562	1550.11694	1550.15500
Source to 99:1 splitter to meter	1550.11575	1550.11531	1550.11564	1550.11694	1550.15502
Source to 99:1 splitter to switch to meter	1550.11579	1550.11536	1550.11565	1550.11696	1550.15509
Δ by adding 99:1 splitter	0.00007	-0.00001	0.00002	0.00000	0.00002
Δ by adding 99:1 splitter and switch	0.00011	0.00004	0.00003	0.00002	0.00009

6.0 ANALYSIS AND CONCLUSIONS

The NKT BASIK lasers appear to have some measureable WL drift during warmup. This warmup drift was measured to be 0.74 pm at most during the experiment. Although this drift would cause less than a 100-m/s upshift drift (1.3 pm) from the intended upshift, it is still recommended that the lasers be allowed to warm up fully before beginning PDV operations. The stability experiment showed that the lasers are essentially stable after 15–20 min of warmup, after which point they may oscillate by up to 0.07 pm. This oscillation is on the order of a 1- to 10-m/s upshift velocity, which is essentially negligible, and, depending on the oscilloscope sampling rate and PDV window size, may even be below the velocity resolution of the PDV system.

The lasers show a small increase in WL with an increase in power. The measured shift resulting from a power increase was 0.67 pm, which is similar to the WL shift that occurs during warmup. Although the drift from the intended upshift would be small (<100 m/s), it is still recommended that WLs be measured with the lasers set to the value intended to be used during PDV operations. For example, if the lasers are to be run at 30 mW, the WL measurement should be performed with them set to 30 mW rather than at a reduced 12 mW where practical.

The bias from the 99:1 splitters and the OZ Optics switch was measured at 12 mW because of the power limitations of the Bristol 228A laser WL meter. Although there was a WL shift because of changing power, there is no reason to expect that changing power would introduce any additional shift with the splitters and switch. Adding the 99:1 splitters caused a negligible shift in WL of -0.01 pm to 0.07 pm depending upon the channel. Because the splitters use single-mode fiber for 1550 nm, this is not particularly surprising, but it does mean that the fusing does not introduce much additional shift. The OZ Optics splitter does add some additional shift for a total shift of 0.02 pm to 0.11 pm depending on the channel. This corresponds to a difference between the measured velocity upshift at the Bristol 228A meter and the actual velocity upshift in the PDV system of less than 11 m/s.

In conclusion, the bias introduced by the in-situ measurement setup, consisting of optical splitters and an optical switch, introduces a real bias compared to a direct connection from the lasers to the WL meter, but it is small (corresponding to <11 m/s velocity in the PDV measurement), and it is likely to be negligible in most HE test setups. Therefore, the in-situ setup can be relied on for setting up upshifted PDV measurements. It is recommended that a laser WL meter be used in place of the NKT control software's reported WL readings, which were inaccurate by upwards of 15 pm (see Table 3) corresponding to a 1450 m/s upshift difference from intended. In most cases, an in-situ setup similar to that at TA-40 Chamber 15 (Figure 3) will provide sufficient precision without the hassle of swapping/cleaning fibers to make measurements. Although the upshift should always be tested by capturing and processing a static reflection before performing the HE test where possible, using a WL meter can significantly cut down on the trial and error setting of the upshift from inaccurately reported WL values.

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