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Ultrafast pulse metrology for industrial applications

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ABSTRACT

The performance of industrial ultrafast lasers with average power ranging from 10-1000 Watts depends on their wavelength, pulse duration, total power, and repetition rate. However, variability in laser performance, despite similar characteristics and manufacturing, indicates the current metrics are not enough. Here we introduce the power figure of merit (PFM), to quantify the power that resides within the short pulses as opposed to the background light, or 'dark energy' between the pulses. We introduce take advantage of linear sampling using photon counting methods to quantify PFM and demonstrate its use on lasers with PFM ranging from 0.9 to 0.995.

Keywords:

1. INTRODUCTION:

The use of industrial ultrafast lasers (iUFLs) is experiencing exponential growth thanks to the promise of non-thermal precision ablation and the recent availability of powerful systems with the repetition rate and reliability required for industrial and medical applications. These lasers differ from those used in scientific experiments because they usually require powers >1 W. Current commercial units provide hundreds to thousands of Watts of power and repetition rates from 100kHz to 100 MHz. These lasers have one or more amplification-stages, are typically compact, and are often fiber based. As the number of applications and commercial lasers increases it has been noted that not all lasers with the same reported characteristics i.e. wavelength, average power, pulse duration and repetition rate, perform a desired processing task with the same efficiency and quality. Anecdotal reports indicate that even lasers that are the same model may not show the same performance. This implies that pulse duration, average power, and repetition rate are not sufficient metrics to characterize an industrial ultrashort pulse laser.

Prior to the emergence of iUFLs, there was little or no need to measure the energy content between laser pulses. Ultrafast scientific applications involve nonlinear optical processes for which the energy between pulses causes little or no background. Here we highlight the need for measuring what fraction of the average power of an iUFL is contained within the actual pulses and how much power is contained in the time between pulses, which we refer to as the 'dark energy'. We propose measuring that fraction, which we call the power figure of merit (PFM). During manufacturing, PFM should allow improvements in order to meet the highest standards of quality and reproducibility. In addition, PFM will allow comparison among the growing number of industrial lasers. Finally, when the lasers are operating in industry or in the clinic, the PFM can serve as a valuable diagnostic that may even predict that a catastrophic failure will occur in the near future. As such, we consider PFM to be a metric that completes iUFL characterization, when added to pulse duration, repetition rate and average output power.

1.1 Technical Difficulties:

Consider a 100 W laser operating at a repetition rate of 1 MHz. If such a laser had a PFM of 1.0, implying all the power is concentrated within the pulses, the only other metric required to predict its performance would be the pulse duration. Now, consider the same laser, however, the PFM is 0.8. That value implies that 20 W of power are dispersed between the pulses. Here we argue that at present, there are no methods capable of determining PFM, especially in the example proposed here. Given that all pulse characterization methods use nonlinear optics, they discriminate against long pulses or continuous emission, and so they go unmeasured. While 20 W seems to be a large amount of energy that should be easy to measure, it is extremely difficult because the intensity of a femtosecond pulse with duration ~ 10^{-13} s is seven orders of magnitude greater than the intensity of the background, which lasts 10^{-6} s. Therefore, for every ten-million photons within the pulse, there is only one photon detected in the background. Such levels would be very challenging to measure with an oscilloscope or a power meter because of their limited dynamic range. While high contrast autocorrelation systems have

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been developed, boasting 10 and 13 orders of magnitude of dynamic range, these systems require high energy pulses and lower repetition rates (<10 kHz). Moreover, autocorrelators have a limited time window of a few nanoseconds and cannot explore the microsecond(s) between the pulses.

Previous attempts to measure the dark energy by modulating the amplitude of the laser via attenuation or chirp while collecting linear, and nonlinear signals, are complicated by the fact that all measurements depend on the introduced attenuation. The main problem of this approach is that the dark energy may be incoherent and evenly distributed between the pulses. Alternatively, it may be in the form of parasitic pulses, which can induce nonlinear conversion. These two possibilities would show a different dependence. Finally, we should also mention that there are new boxcar averaging electronics capable of megahertz measurements that could be used to gate the signal collected by a photodetector while discriminating the pulses themselves. Such an approach would be limited by the nanosecond resolution of the time gate and the sensitivity of the photodetector, which needs to be operated just below saturation in the presence of the intense pulses. This approach could be enough to measure 0.1 mV average amplitude. Assuming the pulses are one volt, 0.1 mV integrated over 7 orders of magnitude would correspond to an integrated signal of 1000V, or a PFM of ~0.001. Clearly, this approach is not very sensitive.

1.2 PFM measurement concept

The principle for measuring the PFM is to take advantage of photon counting technology as a means to non-invasively sample the pulse train. This is novel because pulse characterization typically involves a nonlinear optical process, which would be relatively blind to photons outside the main pulses. The proposed photon counting approach has two key advantages. First, it has an extraordinary dynamic range that is limited only by the time of acquisition. Second, it permits flexibility in the choice of time windows, or bins, where the photons are accumulated. For example, bins can be as short as 10 ps in duration, to encompass the pulse, or as long as microseconds. Furthermore, the photons within bins can be summed in order to count the number of photons within two laser pulses. Based on the definition and equation (1), the number of photons within the first 10 ps, divided by the total number of photons corresponds to the PFM.

$$PFM=\frac{P_{pulse}}{P_{total}}$$

In Figure 1 we show the simulated oscilloscope trace for a laser with a PFM of 0.9, implying only ninety percent of its power is contained within the pulses, the rest is in microsecond(s) between the pulses. If we set the oscilloscope to measure 1V at the peak of the laser pulses, we find that the amplitude between the pulses is on the order of 10^{-7} V and is essentially unmeasurable.

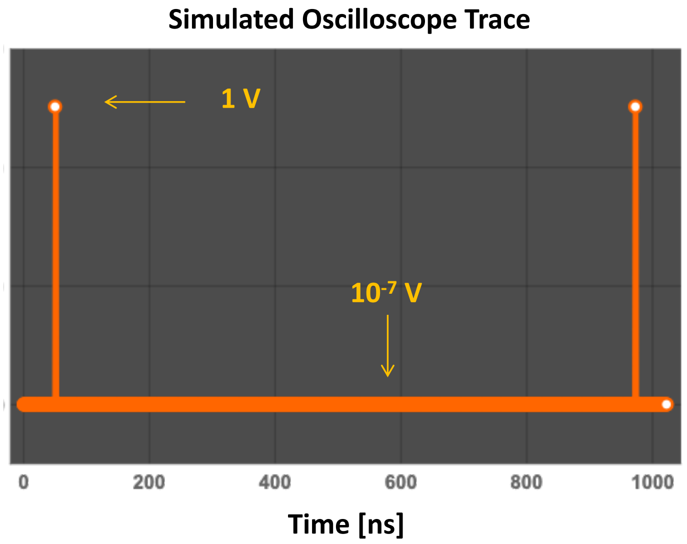

Figure 1. Graphic illustrating the simulated oscilloscope train for a 1 MHz repetition rate 100 W laser with a power figure of merit of 0.9. The vertical corresponds to the number of photons per bin size (here 1 ns), while the horizontal axis illustrates time, here in nanoseconds. Given the 0.9 power figure of merit, we know that 10% of the power is distributed in the time between the pulses. However, that time is so long that the number of photons is too small to be seen on a linear scale.

Figure 2 shows the same train of pulses but in-between it shows the sum of all the photon counts occurring between the pulses. With this sum one is able to quantify the PFM of the laser. The accuracy of the proposed method is only limited by the acquisition time. For example, in one second there are 10^6 pulses, randomly sampled at one photon every thousand pulses, leads to only 10^3 photons counted, if the integral between pulses is one photon, then the PFM would be 1000/1001=0.999. This level of precision requires that one is able to subtract or discriminate for stray room-light photons and dark detector current. Both of these are relatively easy to account for by an additional measurement in the absence of the laser light.

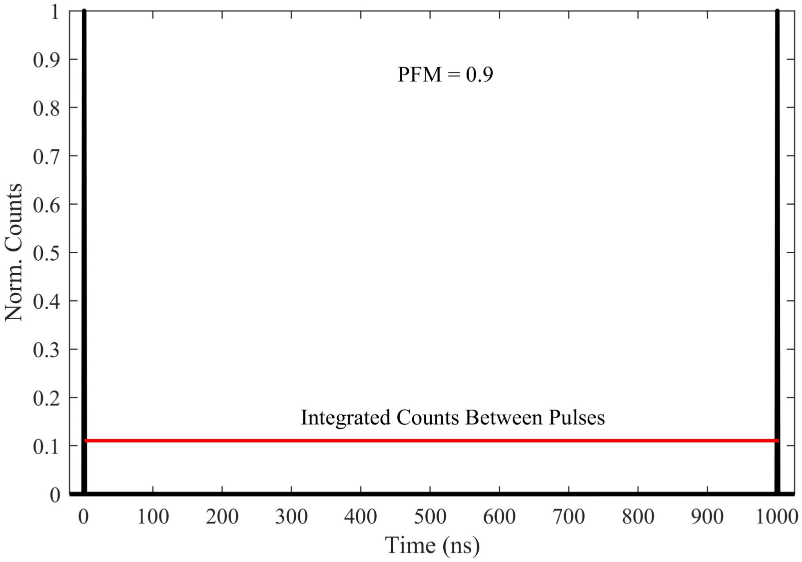

Figure 2. Graphic illustrating how the output of a 100 W laser with a power figure of merit of 0.9 would look with the proposed measurement. The vertical axis is normalized to counts, while the horizontal axis illustrates time, here in nanoseconds. Given the 0.9 power figure of merit, we know that 10% of the power is distributed in the time between the pulses. We see that the black line does not detect the signal because of limited dynamic range, However, the histogram level, the red line, at 0.1 (indicating 10 W), corresponds to the integrated number of photons between the pulses. By seeing the integrated pulse intensity = 1 and the height of the integrated background between pulses = 0.1, we learn that the power figure of merit = 1/(1+0.1) = 0.9.

2. EXPERIMENTAL

The implementation of iUFLs linear pulse-train sampling into a device requires (a) a means to sample the laser, (b) a means to isolate signal from the laser only, (c) counting and binning photons, (d) programmable calculations of the PFM, (d) providing a result in terms of PFM. Given that photon counting devices have been used extensively for optical microscopy, the implementation of part (c) above is well known.

Specifically, we used a time-correlated single photon-counting (TCSPC) system with a compact spectrometer and a 16-photomultiplier tube (PMT) array (SPC-830 TCSPC, Becker-Hickl, GmBH), although much simpler systems would be suitable, to sample a Coherent Vitara Titanium Sapphire oscillator and a home-built fiber laser.[1] A fast diode was used to collect a portion of the beam and serves as a stop for the counting system. The photon counter linearly sampled the laser pulse train at a rate of 1 photon per thousand pulses. We exercised extreme care to reject stray ambient photons by taking advantage of a fiber collection and the small monochromator. We also made sure that the response of the photon counter was linear, as opposed to multiphotonic. A nonlinear response would discriminate against incoherent light and would bias the measurement to the pulses. Leaving a significant amount of dark energy undetected.

Signal collection of a very small portion of the pulse train in the form of scattered light from the edge of a razor blade, allowed us to sample the pulse train. The blade was needed because the two lasers we measured had average power of less than 0.5 W. More powerful lasers would not require the use of a blade to scatter light toward the photon counter. Following data acquisition for a period of time of one to a few minutes, we moved the razor blade out of the way and collected data for a similar period of time in order to establish the background signal in the absence of laser light. Data processing involved integrating the signal between the pulses to establish the dark energy level per unit time. We then integrated the signal under one pulse and subtracted the appropriate dark energy within that pulse duration, assuming that the dark energy is incoherent and present everywhere. We then divided the pulse signal by the total signal, which includes the pulse and the entire time until the next pulse. That ratio gives the PFM according to Eq. 1.

3. RESULTS

Our first measurements were made on a commercial oscillator (Vitara, Coherent Inc). We sampled the 80 MHz train of pulses at both 800 nm and at the second harmonic wavelength (400 nm). The results obtained for 800 nm light are shown in Fig. 3. For these experiments the counter was allowed to reach the maximum number of counts, 2^{16}, which happened after a few minutes. We repeated the measurement five times and five times we counted for the same number of minutes but without the laser scatter. From the data we integrated the dark energy between the pulses, and we include that in the plot. The area under one pulse was normalized to 1. Note that the dark energy is assumed to be present as well under the pulses themselves. There is a small peak approximately one nanosecond after the main laser pulse, this is part of the instrument response and was not taken into account in our calculations. The measured PFM at 800 nm was 0.994 ± 0.001, and the measured PFM at 400 nm, under similar conditions, was 0.995 ± 0.001.

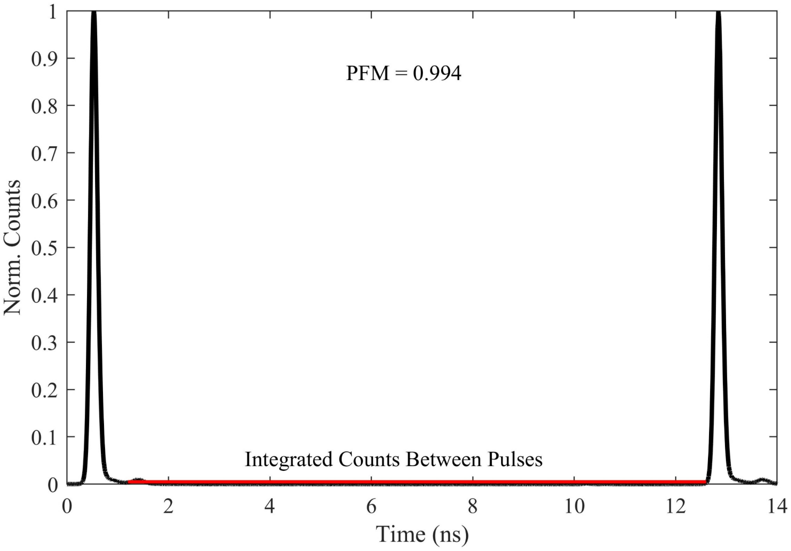

Figure 3. Power figure of merit (PFM) measurement for a titanium Sapphire femtosecond laser oscillator with an 80 MHz repetition rate. The vertical axis is normalized to unity, while the horizontal axis illustrates time, here in nanoseconds. The pulse train (black line) shows the individual pulses. The small glitch 1 ns after the main pulses was not taken into account for our measurement. The integrated level of signal between the pulses is shown in red. For these measurements, the power between pulses accounts for 0.6% of the total energy measured.

For the second set of measurements we used a home-built femtosecond fiber oscillator described elsewhere.[1] Briefly, it is a self-similariton fiber oscillator producing 40 fs pulses at a repetition rate of 41.5 MHz, with an average output power of 0.5 W. The oscillator was mode locked for the measurement, but the output pulses were not optimized or compressed by the MIIPS HD pulse shaper.[2] Given that the photon counter has an instrument response function of ~100 ps, pulse compression would not make a difference. Because the fiber laser output at 1060 nm is outside the sensitivity range of the photomultiplier used in our measurements, we measured the second harmonic output at 530 nm. The results of the measurement are shown in Fig. 4. The second harmonic output of the fiber laser had a PFM of 0.910 ± 0.010, which is significantly lower than for the titanium sapphire oscillator. One possible reason for this being that all the light within the fiber, including light that is not part of the pulses, is emitted by the laser in the same direction.

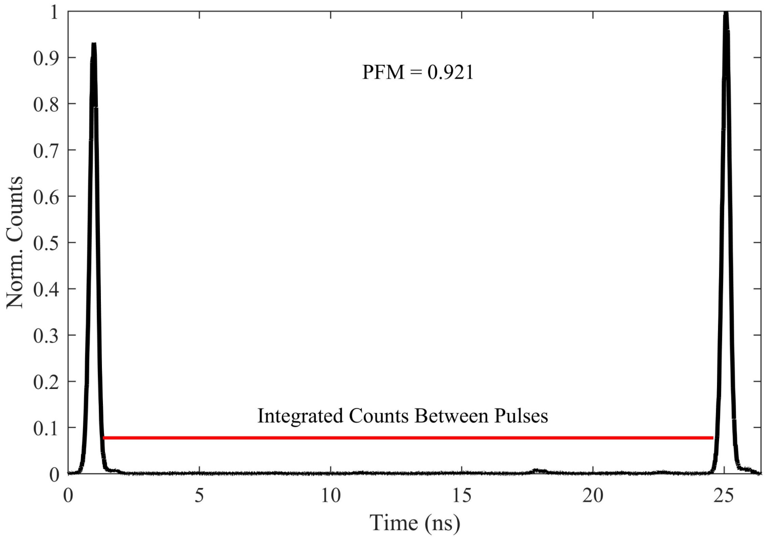

Figure 4. Power figure of merit (PFM) measurement of the second harmonic (530 nm) of a home-built Yb-doped fiber femtosecond laser oscillator with a 41.5 MHz repetition rate. The vertical axis is normalized to unity, while the horizontal axis illustrates time, here in nanoseconds. The pulse train (black line) shows the individual pulses. The small glitch 1 ns after the main pulses was not taken into account for our measurement. The integrated level of signal between the pulses is shown in red. For these measurements, the power between pulses accounts for 8% of the total energy measured.

CONCLUSIONS

Here we introduce linear sampling taking advantage of photon counting technology in order to determine the laser power that resides between pulses, 'the dark energy,' of industrial ultrafast lasers. We presented data for a well-behaved titanium-oscillator, with PFM=0.994, as well as data from the second harmonic of a home-built fiber laser that was not optimized, with a 0.910. The approach proposed and demonstrated provides a solution to determining the energy between pulses for industrial ultrafast lasers. For those interested in laser design or laser diagnosis, it is very instructive to plot the acquired photon counts in a logarithmic scale and to use the smallest bins possible. In this case, one is able to determine the presence of parasitic pulses that have escaped from Pockels cells or pulse pickers. The measurement can be reset, and information can be available to the user in real time. When the laser is in use, PFM measurements can alert the user of degraded performance and provide valuable diagnostics that may indicate trouble before a catastrophic laser failure.

ACKNOWLEDGEMENTS

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