

Methods for Measurement of Pulse Parameters of Fiber Lasers

Lyubomir Lazov
Rezekne Academy of Technology
Rezekne, Latvia
lyubomir.lazov@rta.lv

Tsanko Karadzhov
Technical University of Gabrovo
Gabrovo, Bulgaria
karadjov_st@abv.bg

Edmunds Teirumnieks
Rezekne Academy of Technology
Rezekne, Latvia
edmunds.teirumnieks@rta.lv

Antons Pacejs
Rezekne Academy of Technology
Rezekne, Latvia
antons.pacejs@rta.lv

Conyu Conev
National Military University
Artillery, AD and CIS Faculty
Shumen, Bulgaria
coni19@abv.bg

Abstract. Fiber lasers play an increasingly pivotal role in numerous scientific and industrial domains, spanning from optical communications to medicine. Their utilization across various technological realms continues to surge, prompting the demand for novel physical methods and principles to precisely measure laser pulse parameters during technological investigations. This article provides an overview of contemporary techniques and approaches employed in measuring the parameters of laser pulses generated by fiber laser systems, with a focus on accurately determining pulse frequency and duration. Special attention is paid to the specific measurement of the relationships between frequency, average power, pulse energy and pulse power for a 20W fiber laser source used for laser color marking on stainless steel.

Keywords: Frequency, Pulse duration, Fiber laser, Color marking, Measurement, Laser technology, Pulsed parameters.

I. INTRODUCTION

On the need for accurate pulse characterization of nanofiber lasers for various industrial and medical applications

Accurate characterization of nanofiber laser pulses is crucial for optimizing productivity, increasing process efficiency, ensuring safety, advancing research, and facilitating standardization across various industrial and medical applications (Figure 1). By precisely controlling pulse parameters, industries and researchers can unlock the full potential of nanofiber lasers for a wide range of practical applications. Accurate pulse characterization allows researchers and engineers to precisely control parameters such as pulse duration, repetition rate, and output energy. This optimization ensures that the laser's performance is tailored to the specific requirements of

various applications, including industrial processes such as micromachining and medical procedures such as laser surgery.

Understanding the characteristics of nanofiber laser pulses enables industries to improve the efficiency of manufacturing processes [1], [2], [3], [4], [5]. For example, in laser material processing applications such as welding or cutting, precise control over pulse parameters can minimize heat-affected areas and reduce processing time, resulting in higher productivity and lower expenses.

In modern communications, the use of optical lasers with nanosecond pulses facilitates high-speed data transmission [6]. By modulating the intensity and timing of nanosecond pulses, information can be encoded and transmitted through optical fibers at ultrafast speeds, enabling efficient communication over long distances with minimal signal degradation [7].

Accurate pulse characterization is crucial for ensuring the safety and reliability of laser systems, especially in medical applications. By precisely controlling parameters such as pulse energy and smoothness, medical professionals can minimize the risk of tissue damage and ensure optimal treatment outcomes for patients. Additionally, nanosecond pulse lasers are used in imaging techniques such as optical coherence tomography (OCT) for high-resolution imaging of biological tissues [8], [9], [10].

Nanosecond pulse fiber lasers are also valuable tools in biomedical research for studying cellular and molecular processes. Their ability to deliver high-energy pulses in a controlled manner allows researchers to manipulate and study biological samples at the nanoscale, facilitating advancements in areas such as cell biology, neuroscience,

Print ISSN 1691-5402
Online ISSN 2256-070X

<https://doi.org/10.17770/etr2024vol3.8185>

© 2024 Lyubomir Lazov, Tsanko Karadzhov, Edmunds Teirumnieks, Antons Pacejs, Conyu Conev.
Published by Rezekne Academy of Technologies.

This is an open access article under the [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/).

and drug discovery [11]. Characterization of nanofiber laser pulses provides researchers with a better understanding of the fundamental physical processes involved in laser-material interactions.

This knowledge is essential for developing new laser technologies and advancing scientific understanding in areas such as photonics, materials science, and biomedicine.

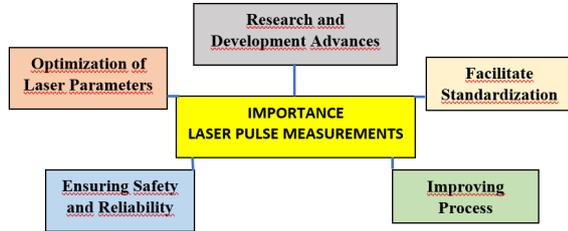


Fig. 1. Accurate characterization of laser pulses is important for various applications in industry, medicine, and research.

Nanosecond pulse fiber lasers are used in spectroscopic techniques for material analysis [12]. By interacting with materials at the nanoscale, nanosecond pulse lasers can induce specific optical and chemical changes, providing valuable information about material properties, composition, and structure. This information is crucial for various industrial and scientific applications, including materials science, nanotechnology, and environmental monitoring [13].

Standardized methods for pulse characterization allow consistency and comparability across different laser systems and applications. This facilitates collaboration between researchers and industries, accelerates the adoption of technologies, and ensures that performance metrics are meaningful and universally understood.

II. GENERAL CONTENT

A. Types of fiber lasers

Due to the specificity of its construction, such as the flexibility of the fiber material used as the active medium, as well as the fiber structure and cavity configuration, there are also many different types of fiber lasers. The fiber core is doped with a different type of active dopant material, usually rare earth elements, and the laser generation is propagated and amplified in the thus doped medium/core. The inner shell and core together direct the pump light, which provides the energy needed for amplification in the core (Figure 2).

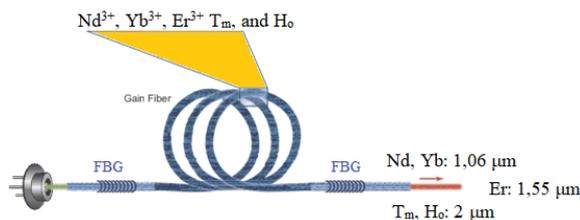


Fig. 2. Varieties of fiber lasers according dopant material.

In fiber laser, there are several widely used ion dopants, such as Nd^{3+} , Yb^{3+} , Er^{3+} , Tm , Ho . Nd- or Yb-doped fiber laser emits laser in $1.06 \mu\text{m}$ wavelength region which is widely used in laser process and laser weapon [14], [15], [16]. Er-doped fiber laser emits laser in $1.55 \mu\text{m}$ wavelength region which is suitable for optical

communication and optical sensing [17], [18]. Tm- or Ho-doped fiber laser emits laser in $2 \mu\text{m}$ wavelength region which is eye-safe and widely used in special laser communication, atmosphere sensing, and medical application [19], [20].

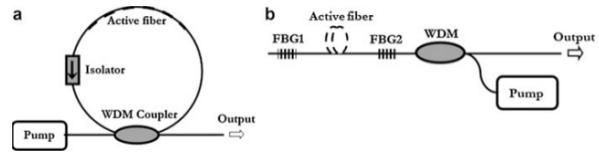


Fig. 3. Ring cavity and linear cavity fiber laser. (a) Ring laser, (b) Linear cavity laser

According to the cavity configuration used, fiber lasers can be classified into ring cavity fiber laser and linear cavity fiber laser [21]. Ring cavity fiber laser (Fig. 2a) usually utilizes an optical coupler and connects its two ends together with a gain optical fiber so that the optical feedback is formed. It is a traveling wave cavity laser and has a relatively long cavity resulting in a small longitudinal mode gap. Usually the separate component is needed in the ring cavity to achieve single-frequency operation [22]. Linear cavity fiber laser (Fig. 2b) usually utilizes the fiber gratings as reflectors replacing the traditional optic reflectors. Since fiber Bragg grating (FBG) can be written in the passive fiber or active fiber directly, the linear cavity fiber laser can be very composite. By adjusting the bandwidth and reflectivity of the FBGs and the cavity length, single-frequency operation is easily obtained in a short-cavity fiber laser. Both distributed Bragg reflector fiber laser (DBR-FL) [23] and distributed feedback fiber laser (DFB-FL) [24] belong to this linear cavity fiber laser.

The fiber lasers can operate in different modes and wavelengths. Because of all these differences, the precise measurement of the characteristics of the pulses generated by the lasers is essential for the wide applications of this type of laser.

B. The relation between the frequency and the duration of the pulses with the energy characteristics of the laser generation.

The pulse-following frequency ν in laser systems, which refers to the rate at which successive laser pulses are emitted (see Figure 4), as well as the duration of each individual pulse play a significant role in determining the overall output energy P_{avg} characteristics of the laser system, which in turn affects the various aspects of laser-material interaction and processing results [25].

Pulse energy refers to the total amount of optical energy contained within a single laser pulse. It is a crucial parameter in applications such as laser material processing, where the amount of energy deposited per pulse influences material removal, ablation, or modification. The relationship between the average laser output power P_{avg} , frequency ν and the laser pulse energy E is defined by the following relationship

$$E = \frac{P_{avg}}{\nu}, [J] \quad (1)$$

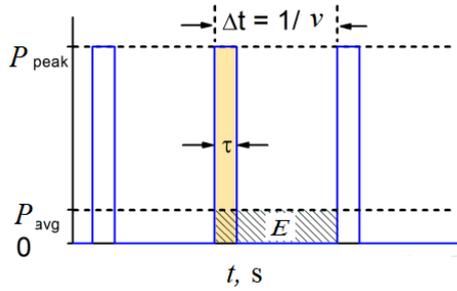


Fig. 4. The graph of the parameters of the laser pulse and the energy characteristics of the laser

Peak power P_{peak} , which is the maximum instantaneous power achieved within a laser pulse, is also affected by pulse frequency ν and duration τ

$$P_{peak} = \frac{P_{avg}}{\nu \cdot \tau}, \text{ [kW]} \quad (2)$$

This characteristic has an important role for processes such as laser cutting, ablation, etc., where a high power density is required for the effective implementation of the specific technological process.

Pulse duration τ refers to the length of time that an individual laser pulse interacts with matter. It determines the time range of the laser pulse and plays a crucial role in processes such as laser machining, where a shorter pulse duration can result in less heat-affected areas and finer resolution. The pulse duration τ is inversely proportional to the spectral bandwidth Δf of the pulse via the uncertainty principle in physics

$$\Delta \tau \cdot \Delta f \geq \frac{1}{2} \quad (3)$$

The uncertainty principle in physics - the product of the time width $\Delta \tau$ and the spectral width Δf of the pulse is a constant quantity.

These relationships and equations help characterize the temporal and energetic properties of laser pulses and are essential for understanding and optimizing laser systems for various applications. Together, they play a critical role in determining the performance, efficiency and suitability of laser systems for various applications [27].

C. Laser pulse measurement methods

This diagram effectively maps out the hierarchy and relationships between different aspects of laser pulse measurement, highlighting the importance of various techniques and tools used in the field. The diagram provides an organized overview of the methods and tools used to measure laser pulse characteristics.

Laser pulse measurements are the central concept, from which all other measurements branch out. They involve a comprehensive assessment of laser pulse characteristics. Duration Measurement: This technique assesses the length of time a laser pulse last. The Autocorrelator determines the width of a pulse by measuring how it interferes with a delayed copy of itself. FROG is a more advanced technique that provides a complete characterization of the pulse.

Two common methods are the Autocorrelator and FROG (Frequency-Resolved Optical Gating). The method provides a detailed temporal and spectral characterization

of a laser pulse. SPIDER (Spectral Phase Interferometry for Direct Electric-field Reconstruction) offers an even more detailed view of the pulse's temporal shape and phase.

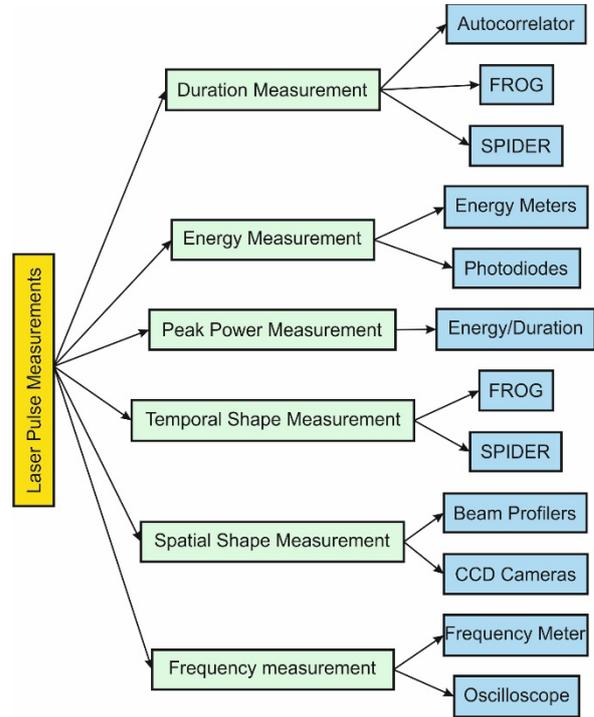


Fig. 5. Laser pulse measurement methods

Energy measurement quantifies the total energy delivered by a pulse. It is divided into two methods. Energy meters measure the energy of laser pulses, while photodiodes indirectly measure the pulse's energy by converting light into electrical current. Peak power measurement calculates the maximum power of a pulse by dividing its total energy by its duration.

Temporal shape measurement is also used, which is divided into two methods FROG and SPIDER. This method investigates the distribution of a pulse's energy across its beam profile. Beam profilers are devices used to capture the two-dimensional spatial intensity profile of a laser beam. CCD cameras, or charge-coupled devices, can image the spatial distribution of laser pulses.

This diagram clearly illustrates the hierarchy and relationships between different aspects of laser pulse measurement, emphasizing the significance of various techniques and tools used in the field.

Based on the methods discussed above, a Laser pulse parameters measurement system has been developed [30].

D. Laser pulse parameters measurement system

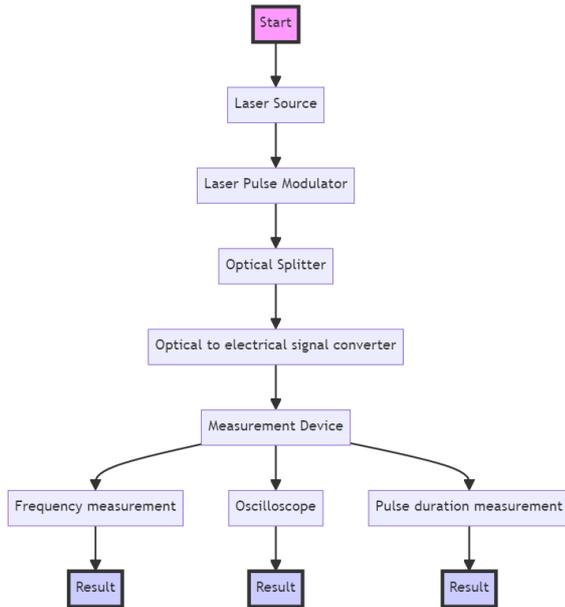


Fig. 6. Block diagram illustrating the laser pulse parameters measurement system.

The system starts with a laser source that generates the laser pulses to be measured [31]. The pulses are then fed into a laser pulse modulator, which adjusts their properties, such as amplitude, frequency, or duration, to ensure they are in the correct form for measurement. Finally, the pulses are directed to an optical splitter. After modulation, the laser pulses pass through an optical splitter which divides the incoming beam into separate paths. One path is sent to the measurement device and the other to a reference or another part of the system. One of these paths goes to an optical-to-electrical signal converter that transforms the optical signal into an electrical one. Measurement devices, such as oscilloscopes and frequency counters, typically operate with electrical signals [32].

Further on describes the measurement devices used to measure various laser pulse parameters. The optical-to-electrical converter feeds the electrical signal into these devices. One of the important parameters that is measured is the frequency of the laser pulses. The measurement of frequency is done using an oscilloscope. Frequency is critical in applications like spectroscopy or laser cutting. An oscilloscope visually displays the waveform of laser pulses, providing information about pulse shape, peak power, and fluctuations over time. The result is a measurement of the time duration of each laser pulse. Pulse duration measurement is crucial for applications where the interaction time between the laser and material is important, such as in materials processing or medical surgeries. Finally, the measurements are collected, and the results can take the form of digital data, printed reports, or visual displays on the measurement devices.

Each step is critical for accurately determining the parameters of laser pulses, which is essential for scientific, industrial, and medical applications. The measurement of pulse repetition rate and pulse duration of laser pulses requires specific instrumentation and techniques tailored to the characteristics of the laser system. For the measurement of pulse repetition rates an optical frequency counter. The counter detects successive pulses and calculates their

frequency based on the time interval between them. Another approach is to use a fast photodiode detector coupled to an oscilloscope to detect each laser pulse and measure the time interval between successive pulses, allowing the repetition rate to be calculated. A photodiode and a frequency counter can also be used. The photodiode converts the optical pulses into electrical signals. These signals are then fed to a frequency meter or frequency counter to determine the repetition rate.

Pulse Duration – Autocorrelation Technique. To measure pulse durations in the femtosecond to picosecond range, an autocorrelation technique can be used. This involves splitting the laser pulse into two beams, delaying one beam relative to the other, and then measuring the interference pattern generated when the beams are recombined. The width of the interference pattern provides information about the pulse duration. **Second Harmonic Generation (SHG):** SHG involves doubling the frequency of a laser pulse using a nonlinear crystal. The pulse duration can be determined by varying the relative delay between the fundamental and second harmonic pulses and analyzing the shape of the generated SHG signal. **Frequency-Resolved Optical Gating (FROG)** is a more advanced technique that measures the spectral and temporal characteristics of the laser pulse simultaneously [28]. The pulse duration can be accurately determined by analyzing the spectrogram obtained from FROG measurements [29].

Measuring the pulse shape, also known as the temporal profile or temporal waveform of a laser pulse, is essential for characterizing its temporal characteristics accurately. There are several methods for measuring the pulse form, each with its own advantages and limitations. Here are some common techniques as photodiode and Oscilloscope. This is a straightforward method where a fast photodiode is used to convert the optical pulse into an electrical signal. The electrical signal is then captured by an oscilloscope, which displays the waveform. This method is relatively simple and provides real-time visualization of the pulse shape. However, it may not be suitable for measuring very short pulses or complex pulse shapes.

Autocorrelation – Autocorrelation is a technique used to measure the similarity between a pulse and a time-delayed copy of itself. In second-order autocorrelation, the pulse is split into two beams. One of the beams is delayed using an adjustable delay line. The delayed and not delayed pulses are then overlapped and sent through a nonlinear crystal. This generates a signal proportional to the autocorrelation function. The pulse shape can be reconstructed by scanning the delay and measuring the resulting signal. This method is commonly used to measure ultrafast laser pulses with femtosecond or picosecond durations.

Frequency-Resolved Optical Gating (FROG) is a more advanced technique that measures both the spectral and temporal characteristics of a pulse simultaneously. It involves sending the pulse through a nonlinear medium and measuring the resulting spectral interference pattern. By analyzing the spectrogram obtained from FROG measurements, the pulse shape can be reconstructed with high accuracy. FROG is particularly useful for measuring complex pulse shapes and ultrashort pulses with femtosecond or sub-femtosecond durations.

For the measurements as a converter of laser pulses into electrical pulses was used High Speed Photodiode Detector.



Fig. 7. High Speed Photodiode Detector for Pulse Laser

He is designed specifically for pulse lasers with a rising edge less than 500 ps. It operates within a wavelength response range of 300 nm to 1100 nm and features a silicon-based detector with a photosensitive diameter of less than 0.5mm. This device is capable of detecting femtosecond, picosecond, nanosecond laser pulses, as well as quasi-continuous and continuous laser or non-laser light sources with high precision. It offers a measurement frequency greater than 1GHz, a rising edge below 300ps, and a falling edge below 500ps, with an output voltage range of 0-12V. The detector requires a power supply voltage of 9 to 24VDC and includes an internal output impedance of 1m ohm, recommending parallel connection with resistors for optimal response speed depending on the pulse width of the laser being detected. This device is versatile, supporting both free space and optical fiber inputs, and is designed to balance bandwidth and output voltage efficiently.

E. Experimental measurements of laser pulses

To measure the frequency of laser pulses according to the algorithm in Fig. 6, a converter with a high-speed photodiode detector, for instance, can be utilized (refer to Fig. 7). This type of converter is suitable for pulsed lasers with a rising edge of less than 500 ps, operating in the wavelength range from 300 nm to 1100 nm. It is capable of detecting femtosecond, picosecond, and nanosecond laser pulses, as well as quasi-continuous and continuous laser or non-laser light sources with high accuracy, even measuring frequencies exceeding 1 GHz.

For the specific scientific study of the laser color marking process using a 20 W fiber laser source "Rofin Power Line F 20" with a wavelength of 1064 nm, calibration measurements of the output laser pulse were conducted. Based on the device and algorithm described in the preceding point, measurements were performed to determine the dependencies between the frequency and the average power of the laser source, the pulse power, and the energy: $P = P(\nu)$; $P_p = P_p(\nu)$; and $E_p = E_p(\nu)$. A PRONTO-50-W5 meter with a range of up to 50 W was employed to measure power, while an E8SP-B-MT-IDR-D0 meter with an RS-232 output, capable of measuring pulse energy up to 0.93 mJ, was used. Both measuring devices encompass a very wide spectral range, including the wavelength of the laser source under study ($\lambda = 1064$ nm). Additionally, the

duration τ of the laser pulse from 4 ns to 200 ns was measured during the study (see figure 8).

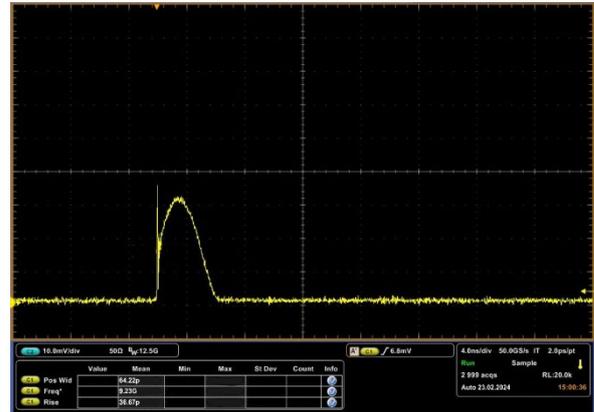


Fig. 8. Oscillogram of laser pulse - 4 ns measured with high speed photodiode detector

The calibration results of the above parameters are presented in Figure 9, Figure 10 and Figure 11.

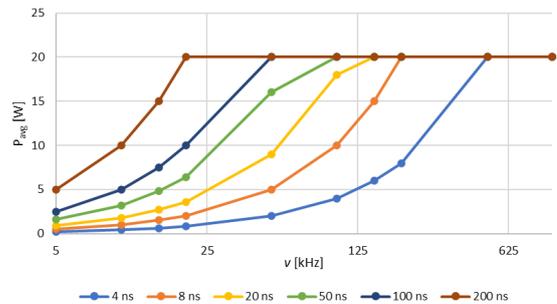


Fig. 9. Functional dependence of average power P_{avg} on pulse frequency ν . The pulse duration is constant in the 4 ÷ 200 ns range.

After analyzing the graphs and studying the characteristics of the laser pulse for the laser color marking process, the following conclusions can be drawn.

The peak power of each focused laser pulse decreases with increasing pulse frequency.

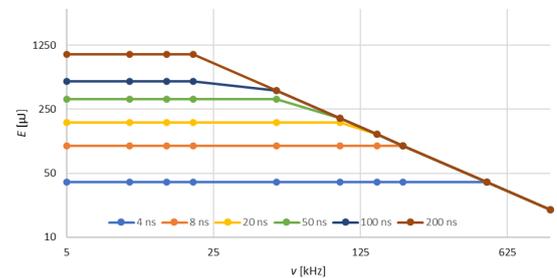


Fig. 10. Functional dependence of impulse energy E on pulse frequency ν . The pulse duration is constant in the 4 ÷ 200 ns range.

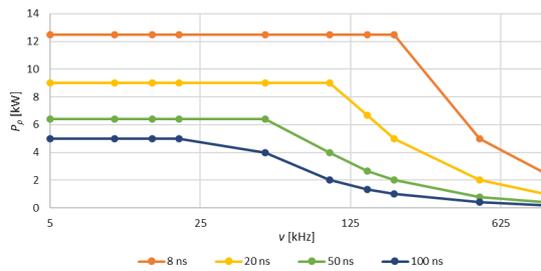


Fig. 11. Functional dependence of peak power P_p on pulse frequency ν . The pulse duration is constant in the $8 \div 100$ ns range.

Since the purpose of laser color marking in the processing zone is to heat it only to the oxidation temperature of the surface and not to vaporize it, lower peak powers (P_p) and higher pulse frequencies are more suitable because they tend to heat the surface of the laser impact without reaching the melting point and vaporization.

By lengthening or shortening the pulse width, as observed in the graphs, the amount of heat on the surface of the part can also be controlled. Making small changes in pulse frequency and pulse width allows for the variation of the thickness of the oxide layer in the laser-affected zone, and these discrete changes in oxide thickness lead to certain color differences.

III. CONCLUSION

In conclusion, this article emphasizes the crucial importance of precise laser pulse measurement in improving the efficiency of fiber lasers in various applications in industry, medicine, and research. It discusses the complexities of fiber laser technology, including the different types of fiber lasers, their modes of operation, and the significance of dopant materials. The paper emphasizes the importance of pulse parameters, such as pulse duration, frequency, and energy characteristics, to optimize laser-material interaction. It describes advanced measurement techniques, including Autocorrelation, FROG, and SPIDER, and provides insights into their applications and advantages for comprehensive pulse characterization. This work contributes significantly to the advancement of the field by presenting a systematic approach to measuring laser pulse parameters. The theoretical material is also supported by experimental evidence. This enables the development of more efficient, reliable, and precise laser systems, fostering innovation in applications that depend on the precise control of laser pulses.

Overall, the analysis provides valuable insights into the relationship between pulse parameters and the laser color marking process. However, there are several areas where the analysis could be improved or expanded:

Quantitative Analysis: While the analysis describes trends observed in the graphs, it could benefit from more quantitative analysis. For example, providing specific numerical values or equations that relate pulse frequency, peak power, and pulse width to surface heating and oxide layer thickness would enhance the clarity and rigor of the conclusions.

Experimental Validation: It would strengthen the analysis to include experimental validation of the conclusions drawn. Conducting experiments to confirm the

effects of varying pulse parameters on surface heating, oxide layer thickness, and resulting color differences would provide empirical support for the conclusions.

Discussion of Limitations: Addressing potential limitations or confounding factors in the analysis would enhance its credibility. For example, factors such as material composition, surface roughness, and ambient conditions could influence the effectiveness of pulse parameters in achieving desired color outcomes.

Consideration of Other Factors: While the analysis focuses on pulse frequency and pulse width, it may be beneficial to consider other factors that could impact the laser color marking process. Factors such as laser power, scanning speed, and substrate properties could also play significant roles and should be discussed if relevant.

Future Research Directions: The analysis could conclude with suggestions for future research directions or areas for further investigation. Identifying unanswered questions or areas where additional research could provide deeper insights into the laser color marking process would add value to the analysis.

By addressing these aspects, the analysis would be strengthened and provide a more comprehensive understanding of the relationship between pulse parameters and the laser color marking process.

IV. REFERENCE

- [1] M. Khorasani, et al., On the role of process parameters on melt pool temperature and tensile properties of stainless steel 316L produced by powder bed fusion, *Journal of Materials Research and Technology*, Volume 12, 2021, p. 2438-2452, ISSN 2238-7854, doi.org/10.1016/j.jmrt.2021.04.043.
- [2] Q. Wang, F. Wang, C. Cai, et al., The essential role of the microstructure and composition in the corrosion resistance of laser-decontaminated surfaces, *Optics & Laser Technology*, Volume 152, 2022, 108111, ISSN 0030-3992, doi.org/10.1016/j.optlastec.2022.108111.
- [3] W. Pacquentin, N. Caron, R. Oltra, Effect of microstructure and chemical composition on localized corrosion resistance of a AISI 304L stainless steel after nanopulsed-laser surface melting, *Applied Surface Science*, Volume 356, 2015, Pages 561-573, ISSN 0169-4332, https://doi.org/10.1016/j.apsusc.2015.08.015.
- [4] M. Stafe, et al., Nanopulsed ablation rate of metals dependence on laser fluence and wavelength in atmospheric air, *U.P.B. Sci. Bull., Series A*, Vol. 70, Iss. 4, 2008, ISSN 1223-7027
- [5] Zhu, Q., Sun, W., Yoo, Y., Zhang, X., Hunter, N., Mao, A., ... & Lu, Y. (2023). Enhance corrosion resistance of 304 stainless steel using nanosecond pulsed laser surface processing. *Surfaces and Interfaces*, 42, 103479.
- [6] Kim, H., Lee, W. J., Farrell, A. C., Balgarkashi, A., & Huffaker, D. L. (2017). Telecom-wavelength bottom-up nanobeam lasers on silicon-on-insulator. *Nano letters*, 17(9), 5244-5250.
- [7] Gupta, S., Engin, D., Puffenberger, K., Litvinovich, S., Kimpel, F., & Utano, R. (2013, September). Fiber laser systems for space lasercom and remote sensing. In *Nanophotonics and Macrophotonics for Space Environments VII* (Vol. 8876, pp. 105-113). SPIE.
- [8] Cusumano, A., Falsini, B., Giardina, E., Cascella, R., Sebastiani, J., & Marshall, J. (2019). Doxycycline honeycomb retinal dystrophy—Functional improvement following subthreshold nanopulse laser treatment: A case report. *Journal of Medical Case Reports*, 13, 1-5.
- [9] Kim, I., Martins, R. J., Jang, J., Badloe, T., Khadir, S., Jung, H. Y., ... & Rho, J. (2021). Nanophotonics for light detection and ranging technology. *Nature nanotechnology*, 16(5), 508-524.
- [10] Chhablani, J., Roh, Y. J., Jobling, A. I., Fletcher, E. L., Lek, J. J., Bansal, P., ... & Luttrull, J. K. (2018). Restorative retinal laser therapy: Present state and future directions. *Survey of ophthalmology*, 63(3), 307-328.

- [11] Vaiano, P., Carotenuto, B., Pisco, M., Ricciardi, A., Quero, G., Consales, M., ... & Cusano, A. (2016). Lab on Fiber Technology for biological sensing applications. *Laser & Photonics Reviews*, 10(6), 922-961.
- [12] Zhang, L., Tang, Y., & Tong, L. (2020). Micro-/nanofiber optics: Merging photonics and material science on nanoscale for advanced sensing technology. *Iscience*, 23(1).
- [13] Georgi Iliev, Hristov H. "Modelling and Simulation of Electropneumatic Positioning System Including the Length of Pneumatic Lines" ENVIRONMENT. TECHNOLOGY. RESOURCES 14th International Scientific and Practical Conference. June 15-16, 2023, Rezekne Academy of Technologies, Rezekne, Latvia, Page 106-111 ISSN 1691-5402 Online IS. DOI 10.17770/etr2023vol3.7186
- [14] Otto, H.-J., Stutzki, F., Modsching, N., Jauregui, C., Limpert, J., and Tünnermann, A. (2014). 2 kW Average Power from a Pulsed Yb-Doped Rod-type Fiber Amplifier. *Opt. Lett.* 39, 6446–6449. doi:10.1364/OL.39.006446
- [15] Wei, H., Chen, K., Yang, Y., and Li, J. (2016). All-solid Very Large Mode Area Ytterbium-Doped Silica Microstructured Fiber Based on Accurate Control on Cladding index. *Opt. Express* 24, 8978–8987. doi:10.1364/OE.24.008978
- [16] Wang, L., He, D., Feng, S., Yu, C., Hu, L., Qiu, J., et al. (2014). Yb/Er Co-doped Phosphate All-Solid Single-Mode Photonic crystal Fiber. *Sci. Rep.* 4, 6139. doi:10.1038/srep06139
- [17] Lv, Y., Lou, S., Tang, Z., Liu, X., and Wang, X. (2020). Tunable C-Band and L-Band Multi-Wavelength Erbium-Doped Fiber Ring Laser Based on a Triple-Core Photonic crystal Fiber with Polarization-dependent Loss. *Opt. Laser Tech.* 128, 106269. doi:10.1016/j.optlastec.2020.106269
- [18] Elahi, P., Kalaycıoğlu, H., Li, H., Akçaalan, Ö., and İlday, F. Ö. (2017). 175 fs-Long Pulses from a High-Power Single-Mode Er-Doped Fiber Laser at 1550 Nm. *Opt. Commun.* 403, 381–384. doi:10.1016/j.optcom.2017.07.072
- [19] Stutzki, F., Gaida, C., Gebhardt, M., Jansen, F., Jauregui, C., Limpert, J., et al. (2015). Tm-based Fiber-Laser System with More Than 200 MW Peak Power. *Opt. Lett.* 40, 9–12. doi:10.1364/OL.40.000009
- [20] Lee, E., Sun, B., Sun, B., Luo, J., Singh, S., Choudhury, D., et al. (2020). Compact Pulsed Thulium-Doped Fiber Laser for Topographical Patterning of Hydrogels. *Opto-Electronic Adv.* 3, 190039. doi:10.29026/oea.2020.190039
- [21] S. Ali, K. A. S. Al-Khateeb and B. Bouzid, "Comparison of the effect structure on Ring and Linear Cavity Lasers of Er-Doped Optical Fibers," 2008 International Conference on Computer and Communication Engineering, Kuala Lumpur, Malaysia, 2008, pp. 546-549, doi: 10.1109/ICCCE.2008.4580663.
- [22] Luna Zhang, Fengping Yan, Ting Feng, Wenguo Han, Yan Bai, Zhuoya Bai, Dan Cheng, Hong Zhou, Yuping Suo, Wavelength-tunable thulium-doped fiber laser with sampled fiber Bragg gratings, *Optics & Laser Technology*, Volume 120, 2019, <https://doi.org/10.1016/j.optlastec.2019.105707>
- [23] Pulov D., P. Tsvyatkov "Optical Systems for Reducing the Divergence of Laser Beams", in. Proceedings of the 14th International Scientific and Practical Conference Environment. Technology. Resources. Rezekne, Latvia, Volume 3, 339-343, 2023, Online ISSN 2256-070X. DOI: 10.17770/etr2023vol3.7217
- [24] Kokalarov, M., B. Sakakushev, S. Parvanov (2021). Generalized Methodology for Application of the Photogrammetric Method for Measurement in Heavy Engineering XXXI International Scientific Symposium Metrology and Metrology Assurance, , IV.3., doi: 10.1109/MMA52675.2021.9610966
- [25] G. Račiukaitis, M. Brikas, P. Gecys, B. Voisiat, M. Gedvilas, et al., Use of high repetition rate and high power lasers in microfabrication: how to keep the efficiency high? *JLMN J. Laser Micro/Nanoeng.*, 4 (2009), pp. 186-191
- [26] Schille, J., Schneider, L. & Loeschner, U. Process optimization in high-average-power ultrashort pulse laser microfabrication: how laser process parameters influence efficiency, throughput and quality. *Appl. Phys. A* 120, 847–855 (2015). <https://doi.org/10.1007/s00339-015-9352-4>
- [27] J. Finger, C. Kalupka, M. Reininghaus, High power ultra-short pulse laser ablation of IN718 using high repetition rates, *Journal of Materials Processing Technology*, Volume 226, 2015, 221-22, <https://doi.org/10.1016/j.jmatprotec.2015.07.014>.
- [28] D.J. Kane; R. Trebino. Characterization of arbitrary femtosecond pulses using frequency-resolved optical gating. *IEEE Journal of Quantum Electronics* (Volume: 29, Issue: 2, February 1993), DOI: 10.1109/3.199311.
- [29] Zhang, H., Fu, M., Chen, X., Qi, J., Yi, W., Zhang, Y., Zhang, Y., Xu, Y., Li, X. Highly precise timing alignment of multi-wavelength interleaved cavity-less pulse sources with FROG (2023) *Optics Express*, 31 (26), pp. 44515-44522. DOI: 10.1364/OE.505879
- [30] Dichev, D., I. Zhelezarov, R. Dicheva, D. Diakov, H. Nikolova, G. Cvetanov. Algorithm for estimation and correction of dynamic errors. 30th International Scientific Symposium "Metrology and Metrology Assurance 2020", September, 2020, Sozopol, Bulgaria. DOI: 10.1109/MMA49863.2020.9254261
- [31] Dichev, D., Koev, H., Bakalova, T., Louda, P. A Gyro-Free System for Measuring the Parameters of Moving Objects. *Measurement Science Review*, volume 14, issue 5, 2014, pp. 263-269. DOI: 10.2478/msr-2014-0036
- [32] Yamada, R., Yamamoto, etc., Correction: Derivation of 1.064 μm normal albedos on the C-type asteroid Ryugu from laser pulse intensity measurement of the Hayabusa2 LIDAR (Earth, Planets and Space, (2022), 74, 1, (166), 10.1186/s40623-022-01717-z) (2024) *Earth, Planets and Space*, 76 (1), art. no. 17, DOI: 10.1186/s40623-023-01949-7
- [33] <https://www.gentec-co.com/>