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Electro-Optical Measurement of Electric Fields for Pulsed Power Systems

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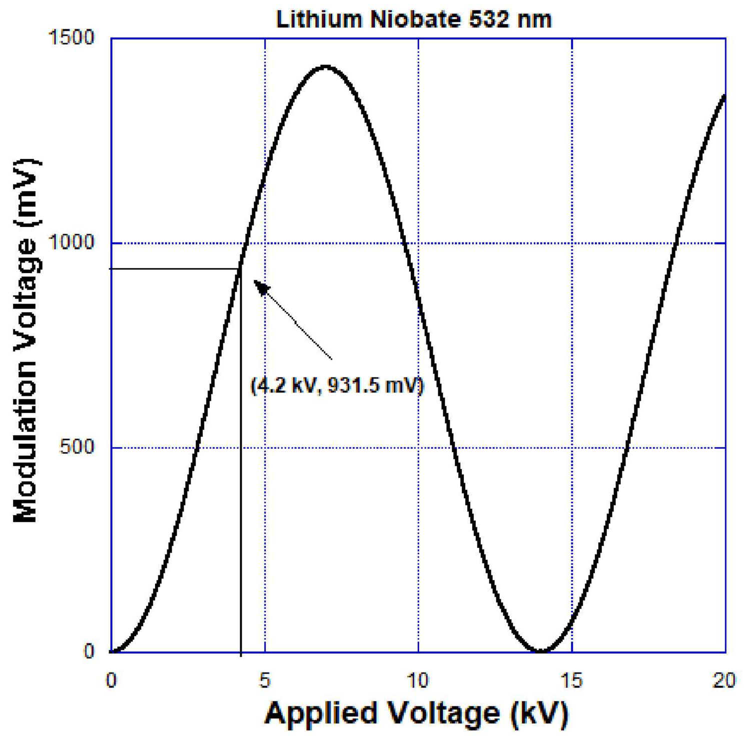
Abstract: The electric field strength between the cathode and anode (i.e., the voltage) of a pulsed power machine is one of the most important operating parameters of the device. However, to date, accurate and precise voltage measurements on these high energy pulsed power systems have proved difficult if not virtually impossible to perform. In many cases, the measurements to be performed take place in an environment cluttered with electromagnetic interference (EMI), radio frequency interference (RFI), and electron pollution, and there is the potential for electrical discharge (or arcing), there is limited physical access, or the measurement area is deemed unsuitable due to radiation safety concerns. We report on an electro-optical-based approach to measuring strong, narrow-pulse-width electric fields that requires no interfering metallic probes or components to disturb the field to be measured. Here we focus on device theory, operating parameters and a laboratory experiment.

Introduction and Motivation

- Electro-optical sensors are ideally suited for noninvasive pulse power diagnostics because they do not suffer from many of the issues of conventional diagnostics.
- Galvanic isolation is important as metallic elements will bring noise back to the readout electronics, and improper electrical impedance matching conditions hamper desired signals with unwanted reflections.
- Electro-optical sensors do not require any integration factors because there exists a direct linear relationship between the electric field and the measured optical signal.
- Dearth of literature on and the use of electro-optical sensors to measure electric field and voltage.
- Sensing fast, high voltage electric field pulses is the least represented.
- Measure the electric field strength of a high energy puled power machine, it is important to consider both the high electric field strength and fast timing requirements. For the HERMES III (HIII) pulsed power machine at Sandia National Laboratories, the peak voltage is 18 MV with an average pulse width of 50 ns.

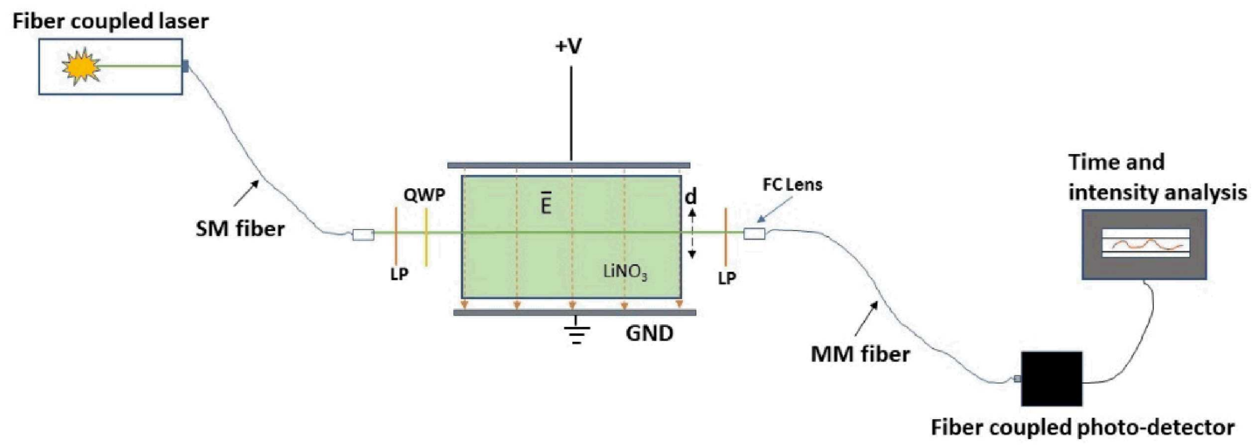
Modeling and Simulation

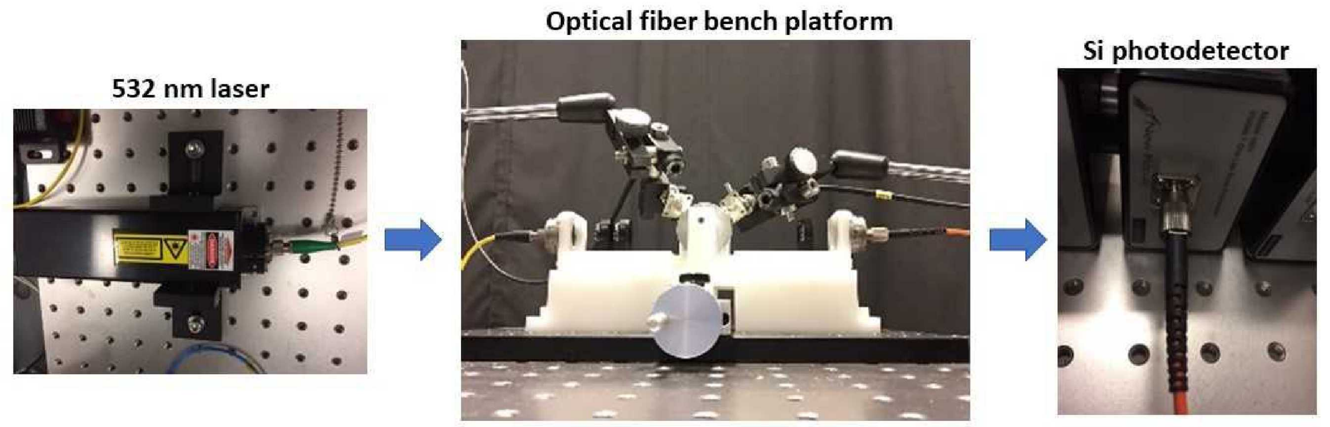
- With a voltage V_a applied across plates separated by a distance d, the shift in the polarization δ_p can be written as: $\delta_p = \frac{2\pi L n_o^3 r_{22}}{\lambda E_3}$ =53.7◦.
- The transmission of light through the crossed polarizers η_c based on the shift in polarization δ_p can be written as: $\eta_c = \sin^2 \frac{\delta_p}{2}$ = 65.4%
- A complete model equation that relates applied plate voltage V_a to the expected output voltage measurement V_m of the photodetector can be written as: $V_m = P_i \eta_c \eta_o \eta_e D_r D_i D_g$ = **931.5 mV**.



Experiment Results and Discussion

- The main components of the experiment consisted of a 250 mW continuous wave single-mode, low-noise 532-nm fiber-coupled laser, a 2.2 ns 4 kV high-voltage pulser, 1 GHz high-speed photodetectors and a custom fiber coupled plastic optical component bench to mount the 25 mm x 6 mm x 6 mm lithium niobate crystal, polarizers, quarter waveplate and 38 mm diameter metal bias plates.
- The circular metal plates were electrically impedance-matched to the high voltage pulser and the oscilloscope to both minimize reflections from the capacitive load and simplify the read out the voltage pulse height amplitude on the oscilloscope.
- From the peak amplitude of both the electro-optical signal and the pulse reference voltage measurements, as well as the other known operating parameters of the system, it is possible to determine the electric field in the vacuum and therefore the voltage applied to the plates.

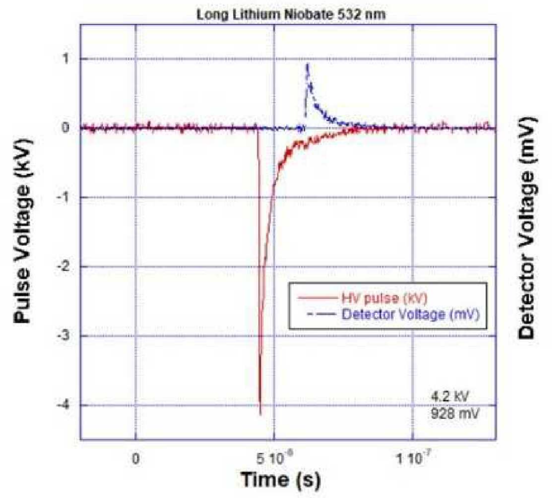




- The peak amplitude, pulse width and leading edges of the electro-optical pulse were within 0.38 %, 2.84% and 5.7 % percent respectively, of the high voltage pulse.
- The electro-optical pulse reproduced both the qualitative shape features and peak amplitude information required to accurately determine the vacuum electric field and voltage bias applied to the plates.
- The laboratory experiment is a scaled simulation of the expected field strength of HERMES III, and reduced concerns about the possibility of dielectric breakdown in the lithium niobate crystal.
- Electron bombardment could be mitigated by placing a protective metal plate adjacent to the sensing side of the crystal.
- For mitigation of radiation darkening, it is possible to position the optical fibers in a region of the radial AK gap that produces the full electric field, but out of direct line of the main particle current flow.
- Lithium niobate has a significant acoustic optical response. Depending on the length of the time record, it was possible to observe the acoustic response on the oscilloscope. However, the acoustic optical response is significantly (100s of ns) later in time compared to the electro-optical signal, and it did not impact the electric field measurement.

Conclusion

- The laboratory experiment essentially simulated the electric field typical of a pulsed power machine such as HERMES III and agreed with the theory and numerical model.
- We demonstrated that it is possible to both accurately measure the electric field in the vacuum, and record the waveform features inherent in the narrow high voltage pulse.
- Future interest includes exploring how different crystal materials, operating (laser) wavelength, and range of voltages affect the electro-optical electric field sensing.
- The next step is to fabricate a compact and ruggedized version of the sensor and perform an experiment on HERMES III to measure its peak voltage.



Acknowledgments

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