A New Electro-Optic Sampling Method Using Two/Multiple Wavelengths

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Abstract
A new electro-optic sampling method is proposed by modulating multiple wavelengths simultaneously to overcome the ambiguity in single-shot pulse application and enhance the signal-to-noise ratio.

Introduction
The traditional method of electro-optic sampling uses a single optical pulse to sample a small portion of electrical pulses. In the proposed method, multiple laser sources at different wavelengths are modulated at the same time. The primary aim is to increase the number of temporal sampling points beyond what can be achieved by conventional methods. To record single-shot events, the optical pulses, at least as long as the electrical transient being measured, are simultaneously present in a fiber-optic-coupled, >16-GHz LiNbO3 EO modulator via a fiber combiner. Besides, the extraction of single-shot, high-bandwidth signal from environments with high levels of electro-magnetic interference (EMI) and ionizing radiation requires that the detection apparatus be far from the measurement point. The isolation of the recording apparatus from the detector can be accomplished by converting the measured electrical signal into an optical pulse and transporting that pulse over a long optical fiber [1,2].

To demonstrate this technique, two lasers with wavelengths at 980nm and 1064nm were fed into the fiber-optic-coupled, >16-GHz $LiNbO_3$ EO modulator at the same time and then separated as shown in Fig. 1. The results can therefore be viewed as a two-beam version of the multibeam sampler. Each pulse is encoded with a distinct replica of the electrical transient as they have very different wavelengths. The measurements made at different wavelengths are independent samples and averaging will increase the signal-to-noise ratio. The improvements in the signal-to-noise ratio progress as the square root of the number of pulses being measured. Each pulse has a different sensitivity to the electrical signal. The transmission of the EO modulator is

$$T_i(t) = \sin^2\left[\pi V(t)/(2V_{\pi i})\right], \qquad (1)$$

where T_i is the transmission coefficient of the EO modulator at wavelength *i*, $V(t)$ is the transient output voltage, and $V_{\pi i}$ is the half-wave voltage at wavelength *i*. If the signal voltage is adjusted so that the peak voltage is less than but approximately equal to $V_\pi(\lambda_0)$ for λ_0 (the longest optical wavelength being modulated), all the lower wavelengths will undergo multiple waves of polarization rotation as $V_{\pi i}$ scales inversely with the optical frequency. Usually, this is undesirable since it leads to ambiguous voltage measurements as shown in Fig 2. However, this ambiguity can be removed as all the wavelengths are modulated simultaneously as illustrated with red curve in Fig 3 (a), where ΔV is the derivative of power-voltage relation function corresponding to the uncertainty of power ΔP . Therefore, the measurement at wavelength where $V_{\pi 1}$ has the lowest ΔV can be used to remove the π-phase jumps at other wavelengths where the applied voltage exceeds their respective V_π thresholds. After combing the voltage errors at two different wavelengths quadratically, see eqn. (5), the ambiguities are removed completely as shown in Fig. 3 (b). The first step in converting the optical signal back to an electrical signal is to do the voltage reconstruction at the lowest optical frequency, giving $V_0(t)$. Next, signals at the higher frequencies are reconstructed. If the external transients do not exceed $V_{\pi i}$

$$V_i(t) = 2a\sin\left\{\left[T_i(t)^{1/2}\right]\right\}V_{\pi i}. \qquad (2)$$

Otherwise,

$$V_i(t) = 2\left\{-a\sin\left[T_i(t)\right]^{1/2} + \frac{\pi}{2}\right\}V_{\pi i} + V_{\pi i}. \qquad (3)$$

The benefit of allowing a given voltage to exceed $V_{\pi i}$ at wavelength λ_i is that it can increase the resolution of the system, where the resolution *R* is defined as the change in transmission due to an incremental change of voltage:

$$R = \frac{\Delta T}{\Delta V} = \frac{\pi}{V_{\pi i}}\sin\left(\frac{\pi V}{2V_{\pi i}}\right)\cos\left(\frac{\pi V}{2V_{\pi i}}\right) \qquad (4)$$

The total voltage error after averaging the errors from two different wavelengths is calculated as the average of the ΔV for two different wavelengths:

$$\Delta V_{total} = \frac{1}{\sqrt{\left(\frac{1}{\Delta V_1}\right)^2 + \left(\frac{1}{\Delta V_2}\right)^2}} \quad (5)$$

An example is shown in Fig.3; where Fig. 3(a) shows the case of two voltage errors plotted versus the transient magnitude. It is seen that near V_π, ΔV diverges, indicating a loss of resolution. However, the lower ΔV sets in, as shown in Fig. 3(b), restoring ΔV to a finite value.

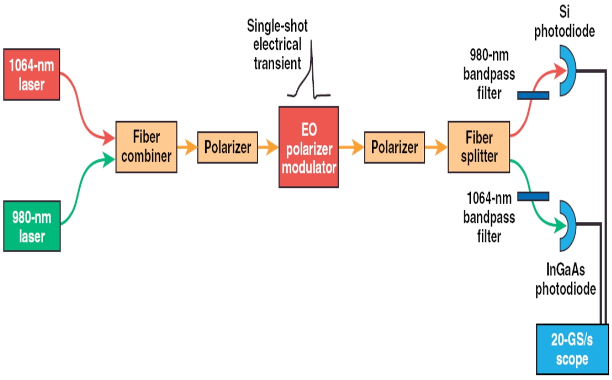


Fig. 1. The multi-wavelength EO measurement system uses off-the-shelf components.

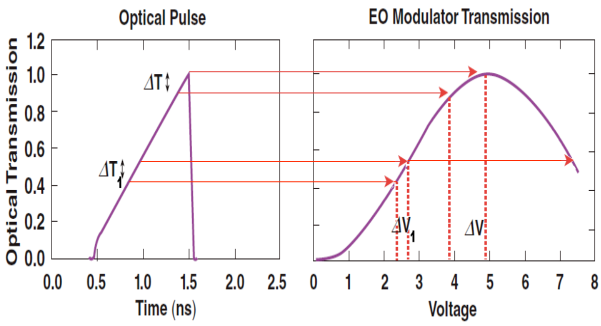
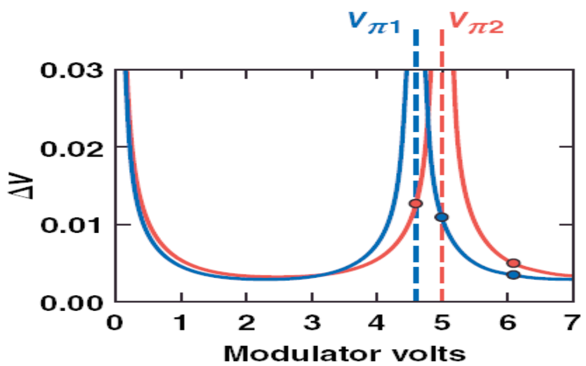
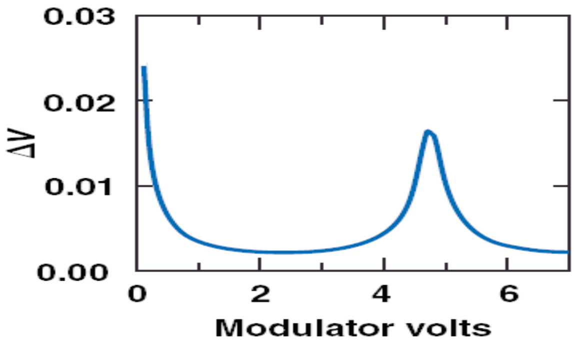


Fig. 2. The Resolution reaches zero at extrama.



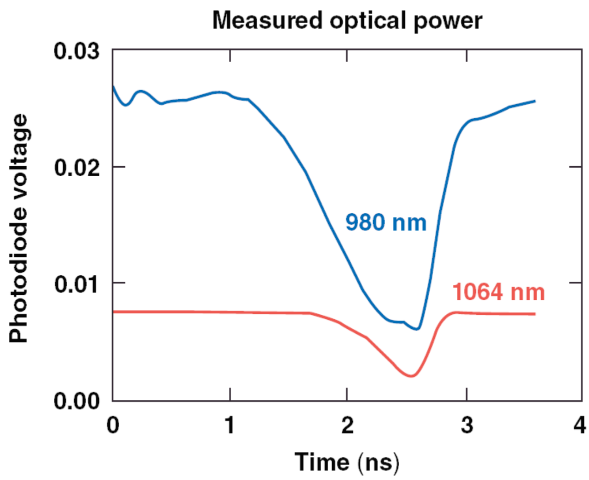
(a)



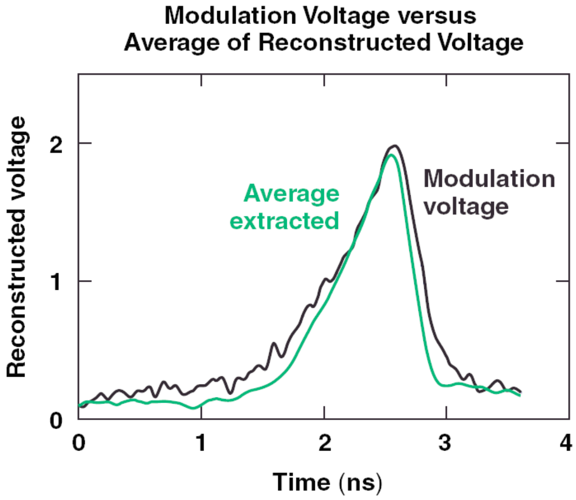
(b)

Fig. 3. (a) Multiple wavelengths can be used to fill in the gaps in the uncertainty of the voltage. (b) The ambiguity could be removed by averaging the voltage error at two different wavelengths.

In our experiments, two lasers, one with wavelength 980nm and the other with wavelength 1064nm, were fed into a 2-by-1 combiner at the same time. Then those pulses were fed into a fiber-optic-coupled, >16-GHz $LiNbO_3$ EO modulator. The measured optical powers from two different wavelengths are shown in Fig. 4 (a). After deconvolution, the signal was reconstructed by averaging the results from different wavelengths. The recovered signal from two different wavelengths closely match the original signal. The accuracy will be improved by using more wavelengths and that is the next step of this experiment. For this case of closely spaced wavelengths, bandpass filters are needed to separate the wavelengths.



(a)



(b)

Fig. 4. (a) The modulated optical waveforms look completely different. (b) The deconvolution indicates that the reconstructed signal is very close to the modulation signal.

There is more work to be done to futher complete the application of this proposed method. Since the SNR is substantially reduced by the EO modulator, a Pulse Replicator could be added into the system to recover this ratio as shown in Fig. 5. The optical pulse is produced by dividing its enery among 256 copies using 2-by-2 fiber-optic couplers. A series of 9 fused fiber couplers are spliced with 1, 2, 4, 8, ..., 256 ns differential delay fibers in between each stage. Each stage produces two pulse sets for input into the next stage. By averagnig the pulse train itself, the SNR is improved. In addition to increasing the SNR of the signal, the optical replicator enhances the high-frequency response of the detected optical pulse beyond what can be achieved in a single measurement. An inverse transfer function is applied to the optical pulse to infer the input electrical pulse as stated above.

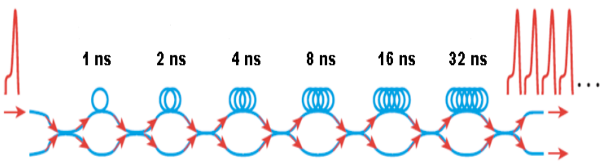


Figure 5. The optical replicator consists of 9 2x2 fiber-optic splitters. At m^{th} stage, one output is directly connected to the input of the following stage. The second output is connected to the second input of the following stage with an optical fiber that has a propagation delay of 2^m times the inter-pulse spacing.

The system shown in Fig. 6 enables single-shot acquisition of electrical transients with enhanced signal to noise ratio. It also provides optical isolation between the detector and the electronic recording device. The isolation feature makes these systems particularly useful for large, low-repetition-rate, laser systems like OMEGA-EP[6] at the University of Rochester that can generate single-shot, picosecond-scale events in an environment with high levels of EMI and ionizing radiation [3].

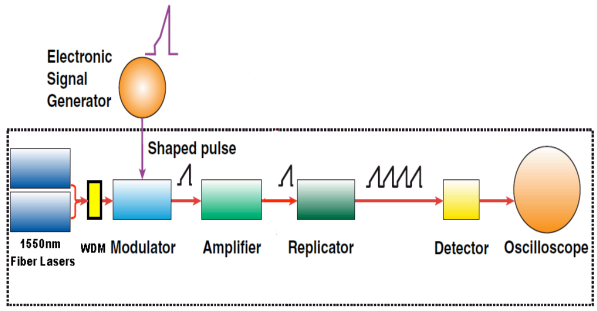


Fig. 6 The next step of the system.

Although used to demonstrate the characterization of the electrical input via the optical output signal, this system was designed inject optical pulses into the front end of the OMEGA Inertial Confinement Fusion laser system. Well characterized electrical pulses are used to produce stable optical pulses. A stand-alone measuring system would probably use a much simpler, cheaper and less-energetic fiber amplifier in place of the regenerative amplifier. An even better solution would be to move the amplifier before the modulator or incorporate as part of the input laser to eliminate the possibility of amplification which induces optical pulse shape distortion. The distortion induced by the regenerative amplifier can be characterized by a single parameter, the square pulse distortion (SPD) [3].

Conclusions

This work demonstrates an EO measurement system that, using commercially available fiber optic and integrated optic components, simultaneously modulates an optical pulse train with different wavelengths. This system is particularly useful for single-shot measurements, where the high DR and SNR of optical pulse insures that the inferred electrical pulse shape has a higher SNR than an electrical pulse directly measured with a conventional electronic oscilloscope. The optical isolation makes the system well-suited to environments with high levels of EMI.

References

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