Application of Wavelet Transform for Analysis of Radiated Electromagnetic Interference in a High Power Terawatt Laser Setup

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Abstract
This paper reports the wavelet transform based time-frequency-intensity analysis of radiated electromagnetic noise generated by a flash lamp pumped terawatt class of high power pulsed laser. High power pulsed solid state lasers are widely used for research and industrial applications. Main electrical components of these lasers are flash lamp power supplies, electro-optic switches, timing and synchronization circuits, and control system. These sub-systems operate at different instants of time during the laser operation cycle. Range of the time delays between switching of various blocks in the system vary from 100 ns to hundreds of microseconds. The electromagnetic noise generated by the laser is pulsed type single shot event, which is measured in time domain. The conventional technique of Fourier transform generate frequency spectrum of the electromagnetic interference (EMI), however, it loses the time information and does not reveal the noise contributions by each of the sources and subsystem localized in time. In this work, wavelet transformations are applied on the measured signals to estimate frequency content of the noise contribution by each source and to generate the time-frequency information. This technique helps in better identification and characterization of the electromagnetic noise sources in a high power laser chain and to achieve the growing demands for electromagnetic compatibility (EMC).

Keywords: Wavelet Transform; Flash Lamp Pumped Solid State Laser; Electromagnetic Interference (EMI)

1. Introduction
Flash lamp pumped high power pulsed solid state lasers are electrically large and complex systems consisting of several laser amplifier stages, timing and synchronization circuits, and electro-optical components. These stages are synchronized by a master clock and are activated at different instants of time with respect to the main trigger signal. Each of the laser stage is a source of pulsed EMI and emits a specific band of frequencies. The wavelet transform based noise analysis described in this paper is carried out for a Table Top Terawatt (TTT) laser system. The TTT laser system is based on chirped pulse amplification scheme (Naik et al., 2003). Main stages of the laser are a pulse selector, flash lamp based laser amplifiers, a pulse injector and a pulse ejector stage. The pulse selector, pulse injector and pulse ejector stages are based on electro-optic Pockels cell switches in which the light polarization are switched by applying high voltage and fast rise time biasing. Fast rise time MOSFET switches of pulsed and step types are used to generate biasing voltages of 3.5 kV. The traditional time domain noise measurements followed by Fourier transform analysis is not adequate to correlate the noise spectrum with specific noise sources or the time instants in this type of a system. The relatively new technique of continuous wavelet transform (CWT) is applied to determine the time-frequency relationship of the noise emission and to identify the sources of EMI. Wavelet transform and its variants have been implemented to analyze EMI in switched mode power supplies, electrostatic discharges etc. (Coppola et al., 2005), (Masugi, 2003). However, no significant work is reported on wavelet application for noise analysis in high power laser systems, which contain multiple noise emitters triggered at different instants of time. The electromagnetic noise emitted by the flash lamp trigger circuits and the high voltage and high speed MOSFET switches in the terawatt laser are measured in time domain by a 10 GS/s sampling digital oscilloscope. The continuous wavelet transform coefficients generate time-frequency-intensity information. The wavelet transformations in this work are carried out on the EMI data from the terawatt laser system under the following two operating conditions.

• The flash lamps trigger signal is followed by the pulse selector event after an interval of around 360μs. This in turn, is followed by the pulse injector and the pulse ejector triggers with an interval of 100 ns each.

• The flash lamp trigger signal is followed by a pulse selector trigger after 360 μs as in the first case above. However, the time delays between the pulse selector-injector and injector-ejector stages are set to 200 ns each.

2. System Description and EMI measurement
2.1 System Description
The table top terawatt laser system generates intense laser pulses of femtosecond duration. It is used to study laser plasma
interaction at ultra-high intensities (1018 W/cm²). It consists of
a mode locked master oscillator operating at 100 MHz repetition
rate, a pulse selector circuit which selects a single laser pulse
from the 100 MHz train in synchronization with an external
trigger, a flash lamp pumped regenerative laser amplifier,a pulse
injector and a pulse ejector electro-optic switch. The basic setup
consisting of these blocks is followed by a single pass and a
double pass laser amplifier for further gain enhancement. The
laser amplifiers are based on flash lamps, which are high current
broadband light sources, and need high voltage trigger signals.
The pulse selector, pulse injector and pulse ejector stages consist
electro-optic switches, which are built around Pockels cellsand
in turn are biased by high voltage high speed MOSFET switches
different switching parameters(Becker et. al, 1994). Physical
layout of the main sources of EMI i.e. the regenerative amplifier,
pulse selector switch, pulse injector switch and the pulse ejector
switch of the Table Top Terawatt laser is shown in Fig.1. These
stages operate under a centralized PC based control system (Singh
et al., 2006) as shown in Fig.2. The pulse selector circuit selects
a single pulse from the laser oscillator operating at 100 MHz. It
consists of a double Pockels cell and two crossed polarizers. The
input polarizer is parallel to the polarization of the oscillator pulse
and the output polarizer is perpendicular to it. A 5 ns pulse of 3.5
kV pulse generated by a MOSFET switch drives the Pockels cell
to rotate the polarization and allow a single laser pulse to pass
through the output polarizer for injection into the amplifier stage.
The regenerative amplifier consists of a Nd: phosphate glass rod as
an amplifying medium, which is pumped by two flash lamps. The
flash lamp power supply consists of a charging circuit, a capacitor
bank and a trigger circuit. Application of a high voltage flash lamp
trigger pulse results into breakdown of the filled gas and lowering
of the conductivity. As a result, the stored energy on the capacitor
bank is discharged through the flash lamps and a pulsed current of
approximately 600 μs pulse duration flows through the discharge
network. Flash lamp current amplitude and width depends on
the capacitor voltage and the circuit parameters. The flash lamp
optical pulse pumps the gain medium resulting into amplification
of the low energy single laser pulse which was selected from the
oscillator by the pulse selector stage.

**Fig.1. Section of the high power Terawatt Laser System**

The injector stage consists of a polarizer and a Pockels cell. The
pulse injection process begins with application of a high
to low going step of quarter wave voltage (3.5 kV) through a
MOSFET switch on the Pockels cell. It injects the laser seed pulse
in the regenerative stage for several round trips and consequent
amplification. The ejector stage consists of a Pockels cell and a
plate polarizer. A fast rising (1-2 ns) step pulse of 3.5 kV is applied
to the Pockels cell, which rotates the plane of polarization, and the
amplified pulse is ejected out.

**2.2 Time Domain EMI Measurement**

The Table Top Terawatt laser operates in single shot mode. The
complete operation of pulse selection, injection, amplification and
pulse ejection takes place in around 600 μs. The EMI generated by
various components in the laser system is transient in nature and
occurs at different instants of time. The flash lamp power supplies

**Fig.2. Laser Control System Block Diagram**

and high voltage drivers for the electro-optical switches generate
random and non-stationary interference signals. Time domain
measurement is most suitable measurement technique for this
type of systems. Fig.3. shows the radiated EMI measurement
setup. A calibrated commercial bi-conical antenna is used to
measure the radiated emission. The measured signal is sampled

**Fig.3. The EMI measurement setup**
by a digital storage oscilloscope with a sampling rate of 10 GS/s (Lecroy waverunner 6100). Mathematical techniques like FFT and wavelet decomposition can be applied on the sampled data for frequency domain conversion and analysis. A MATLAB based wavelet routine is executed on the sampled data to generate the time-frequency-intensity information.

3. Continuous Wavelet Transform Analysis, Discussions and results

3.1 Wavelet Transform

Wavelet transform is a mathematical tool used in many areas of signal processing for time-frequency-intensity analysis (Daubechies, 1992). The continuous wavelet transform for a signal \(X(t)\) is given by,

\[
W(S, \tau) = \left| \frac{1}{\sqrt{|S|}} \int X(t) \psi\left(\frac{t-\tau}{S}\right) dt \right|
\]

\(\psi(t)\) is known as mother or kernel wavelet. The wavelet functions are derived from the mother wavelet through translation and scaling. The parameter ‘\(\tau\)’ is the translation parameter of the wavelet function as it shifts through the signal. The term ‘\(S\)’ is the scaling parameter. Larger scales correspond to low frequencies and it dilates the signal to reveal detailed information. Smaller scales compress the signals. For each value of ‘\(S\)’ the mother wavelet is scaled by a factor of \(1/S\) and translated by ‘\(\tau\)’ to produce the wavelet co-efficient \(W(S, \tau)\). Thus, the wavelet transform decomposes a 1-D time-amplitude signal into a 2-D time-frequency-amplitude information. This is in contrast to the Fourier Transform, which is a 1-D frequency-amplitude transformation. The necessary conditions for mother wavelet are finite energy \(\int |\psi|^2 dt < \infty\) and band-limited \(\int \frac{|\psi(\omega)|}{\omega} d\omega < \infty\). There are several kernel wavelets in use. The Morlet wavelet (Torrence & Compo, 1998) is suitable for transient non-stationary signals and is used in this work. It is given by,

\[
\psi(t) = \frac{1}{\sqrt{\pi}} e^{\omega_0^2 t^2} e^{i\omega_0 t}
\]

\(\omega_0\) is the central frequency with value greater than 5.

3.2 Discussions and results

The Terawatt laser operation cycle starts with charging of the regenerative amplifier power supply and triggering of the flash lamp to initiate gain build up in the amplifier stage. The initial high voltage flash lamp trigger signal is a good source of radiated EMI. The pulse selector circuit is activated 360 \(\mu s\) after the flash lamp trigger signal to coincide with peak of the amplifier gain. Triggering of the MOSFET switch used in this stage generates the fastest rise time, high voltage trigger resulting into a severe EMI. The timing diagram for these events is shown in Fig.4.

The instant ‘A’ marks triggering of flash lamps with a high voltage (10 kV) signal of 5 \(\mu s\) duration. This causes the discharge of the energy stored in power supply capacitor bank through the flash lamps. The instant ‘B’ coincides with peak of the flash lamp current and it also marks operation of pulse selector circuit. The point ‘C’ marks operation of the pulse injector stage which is based on Pockels cells driven by a step type of MOSFET switch. The instant ‘D’ represents operation of pulse ejector stage after several round trips in the amplifier cavity. The terms \(\Delta t_1\) and \(\Delta t_2\) represent the variable delays. These four stages are main sources of EMI noise. Each of these events is accompanied by radiated noise of varying magnitude and frequency. For this type of time distributed complex system, the wavelet transform is an effective tool as it resolves the electromagnetic noise in time-frequency-intensity domains which is easier to analyze and correlate with the noise sources. Fig.5 shows wavelet transform of the radiated electromagnetic noise when the time delay between the pulse selector, injector and ejector stages \((\Delta t_1\) and \(\Delta t_2\)) are set to 100 ns.

Fig.4. Timing diagram of the trigger signals

Fig.5. CWT of the radiated EMI for the injector and ejector delays set to ~ 100 ns.
The first noise instant ‘B’ occurs due to the pulse selector Pockels cell driver switch. The transform shows ringing and oscillations because of the cable length effects. Intensity of the EMI due to injector switch occurring after around 100ns ‘C’ is quite low as it is generated by a step type of MOSFET switch. The most intense EMI is from the ejector stage after a delay of 200 ns from the pulse selector switching ‘D’. This noise is caused by a fast rising (1-2 ns) switch. The analysis is carried out for up-to 1 GHz emission and it is observed that most of the frequencies in this band are present during the switching operations. Fig.6. shows wavelet transform for the noise emission from the laser system with the delays (Δt1 and Δt2) set to 200 ns.

set to ~ 200 ns

Fig.7. shows wavelet transform of the radiated EMI signal generated by triggering and firing of the flash lamps ‘A’. There is significant noise during initial period of the flash lamp activity. This corresponds to high voltage triggering of the lamps. The main flash lamp discharge current which takes place after the trigger event and extends for around 600 μs does not significantly contribute to the radiated emission.

4. Conclusion

Wavelet transform is used to analyze the radiated electromagnetic interference from different components in a high power flash lamp pumped Table Top Terawatt laser. With this method, it is possible to observe the noise emission from individual components on a time-frequency-intensity plot. The radiated noise is generated by triggering of high current discharge of flash lamps and high voltage, high speed MOSFET switches at pulse selector, pulse injector and pulse injector stages. All these events are synchronized in time. The EMI from flash lamp discharge is mainly localized during the initial high voltage trigger process. The radiated EMI from the intermediate stages of pulse selector, pulse injector and pulse ejector stages have different characteristics, depending upon the timing parameters of the MOSFET switch used for the Pockels cell driver in that particular stage. It is more intense in the ejector stage where the switch is of pulsed type and has low rise time. The noise from the injector stage is less intense as it is generated from a step type of MOSFET switch having low rise timing parameters. Intensity of the selectortage noise interference is of intermediate value. Wavelet transform based analysis provides an overview of the electromagnetic noise generated by various components and stages in a high power laser chain. This analysis is helpful towards attaining a better electromagnetic compatibility of the laser system.

5. References


