TIMING AND SYNCHRONIZATION OF A SOLID STATE PULSED POWER MODULES (SSPPM) FOR EXCIMER LASER APPLICATIONS

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Abstract

In certain applications for excimer lasers, it is critical to maintain the timing of a Solid State Pulsed Power Module (SSPPM) such that the pulsed output of the laser can be synchronized to another external event. In some cases, this synchronization must be held to times on the order of 10 ns or less. Since the operating voltage range of these magnetic modulators must vary (by up to a factor of two) in order to adjust the laser output energy, the throughput delay can also vary significantly. This timing must also be maintained over other possible laser operating conditions and scenarios, including various repetition rates, duty cycles, etc. External factors, such as cooling water temperature and flow rate, air temperature, etc. can also impact the system timing. Data will be presented detailing the contribution of each potential item in the timing sequence of these modulators as they impact the overall system timing jitter and drift. Design details will also be discussed as to how these issues are mitigated and minimized so as to reduce their effect and meet the overall system timing requirements

I. BACKGROUND AND REQUIREMENTS

In the recent past, CYMER has embarked on a radically different design philosophy for implementation on upcoming excimer laser systems [1]. Since the requirements for a lithography light source are increasing in average power and decreasing in bandwidth, the design requirements are getting tougher and tougher to accomplish. In the past, average power increases have been met by simply increasing the rep-rate of the laser (with the same approximate energy per pulse). The current generation product line now operates at 4 kHz rep-rates. Unfortunately, decreasing the bandwidth of the laser also tends to reduce the electrical-to-light conversion efficiency. Several other factors also complicate the design, requiring more input power to the laser. For example, the power needed for the laser chamber blower motor is proportional to the cube of the rep-rate. As a result of all of these issues, this previous approach of increasing rep-rates to achieve higher average power levels is simply prohibitive.

The solution to this problem is the use of a MOPA (Master Oscillator Power Amplifier) configuration where two separate laser chambers are used. The Master Oscillator (MO) provides the extremely low bandwidth (~0.2 pm FWHM) required of the final laser light pulse. The Power Amplifier (PA) simply amplifies the light from the MO, increasing the energy per pulse to levels necessary to produce the required laser power levels (40 to 80 W) at rep-rates of 4 kHz.

Experiments conducted over the last several years at CYMER have proven the viability of this concept. The implications of this design approach on the laser power system are the requirement for two "separate" SSPPM systems which must drive the MO and PA laser chambers. The output of these units must also be tightly synchronized in time since the laser pulse output is extremely sensitive to this timing. The present design goals for the system are to hold the timing of the two pulses to within ± 5 ns of the target timing. It is also necessary that the PA pulse be delayed from the MO pulse such that the PA chamber is energized with the arrival of the MO light pulse (~25-50 ns after the MO pulse is generated).

This tight timing requirement must be met over all operating conditions. The operating voltage of these lasers typically increases by a factor of 2 over the lifetime of the laser chamber. In addition, tight requirements of the laser dose mandate that the voltage is adjusted from pulse to pulse in order to minimize pulse energy variations. As a result, the SSPPM initial charging voltage can vary ~30 V from pulse to pulse and from 600 V to 1200 V over the chamber lifetime. The timing must also be maintained over all other possible scenarios, many of which can affect the system timing. These issues will be discussed in the next section.

II. SOURCES OF TIMING VARIATION

Factors which can influence magnetic modulator pulse propagation delay include primary switch jitter, main power supply voltage regulation, bias power supply regulation, temperature related effects, and other more subtle factors [2].

Previous experiments at CYMER have identified the primary cause of timing jitter in the current generation SSPPM design as main power supply voltage regulation. The sensitivity of this factor can vary from 3 to 8 ns per volt over the operating voltage range of the laser. These SSPPM modules typically operate in the ~1000 V (charging voltage) range and the current state-of-the-art in charging systems typically yields pulse-to-pulse voltage regulation of ~± 0.15%. As a result, this implies that the pulse-to-pulse voltage variation can be as much as ~3 V and therefore cause a timing shift of ~10-20 ns. Since two independent SSPPM systems are required for MOPA operation and we require relative timing better than ± 5 ns, this will clearly necessitate some mitigation approach.

Although magnetic switch bias current regulation was also identified as a potential cause for pulse-to-pulse timing variations, no conclusive results were found during the initial experiments to indicate it was a strong contributor to jitter. Regulated power supplies and circuit filtering had been implemented in all SSPPM designs and were thought to be sufficient, at least for the previous timing requirements. Voltage reflections remaining within the SSPPM after the main pulse generation can also cause timing fluctuations in magnetic modulators. In this case however, an energy recovery circuit tends to ensure that the vast majority of this energy is recovered back onto the initial storage capacitor [3] or into the resonant charging system where the effects on switch saturation times would be minimized, if not completely eliminated. Primary switch jitter, using properly triggered IGBTs or SCRs, is typically in the sub-ns range and is therefore not a significant issue in these designs.

All other potential sources of timing variation are typically categorized as "slow". These would include temperature changes in the switch magnetic cores (which can affect the allowable flux swing and therefore saturation time) and long term power supply voltage drift. Since these changes are much slower in nature, they are usually much easier to compensate for.

Finally, it should be noted that most of the concern is with the initial magnetic switch since its saturation time (typically ~4-5 μs) is almost an order of magnitude longer than that associated with the second switch (a few 100s of ns). As a result, any effects which cause a percentage variation of that longer saturation time will result in a larger overall timing effect.

III. SSPPM DESIGN PHILOSOPHY

CYMER's approach to minimizing timing issues includes multiple mitigation techniques. To address the slower, simpler timing "drift", we are implementing an active, closed-loop, control system which will monitor the system timing and adjust the trigger timing between the two SSPPM systems. A "first pulse exclusion" from the customers will allow an initial data point to "calibrate" the controller for each burst of pulses after the laser has been idle. This approach will compensate for start-up transients where the initial state of the system is not well known prior to the first pulse (e.g. the magnetic switch temperatures). In addition, the controller will also adjust the timing based on the voltage target for the next succeeding pulse much the same as other previously employed delay compensation techniques [4-6]. The algorithm used for timing correction in the controller can also be optimized to minimize the timing variation.

Because the MOPA design depends upon relative timing between the MO and PA SSPPMs, the simplest approach to dealing with charging voltage regulation issues is to use a common charging system for both SSPPMs, as shown in Figure 1. A single power supply and resonant charger module therefore charges both SSPPMs to the same initial voltage.

In addition to these design approaches, we intend to also address several other issues which can help control the synchronization of the two pulses. Careful thermal management of the two modulators will minimize temperature changes in the magnetic cores which can result in timing shifts. Making these temperature fluctuations consistent between units will be most important since it is the relative timing that is critical for MOPA operation. Shortening the initial pulse generation time (and therefore the overall throughput delay) will also help the design since any percentage change in timing (due to any external effects) will result in a smaller overall jitter. Increasing the bias current level will help since this will push the core further into negative saturation where it is less sensitive to bias regulation (the change in Delta-B with changes in bias becomes less as the core is driven further and further into reverse saturation). Finally, careful selection of magnetic materials can also assist the design since some materials require lower bias drive levels. As a result, for the same bias, they can be driven further into saturation where these same advantages can yield positive results.

IV. EXPERIMENTAL DATA

A variety of experiments have been conducted so far with the SSPPM and the MOPA systems. Initial investigations showed that although steady state relative jitter of less than 5 ns could be achieved, transients during burst mode operation made the timing much worse. Data from these sets of experiments are shown in Figure 2. The primary cause for these variations was eventually traced to the opto-isolator module used in the previous IGBT trigger circuit. The throughput delay of this component not only varied with temperature but also with rep-rate. The oscilloscope display in the figure is triggered by the SSPPM input trigger and the timing of the expanded output voltage trace is measured with the histogram function by setting the histogram window at a position on the output voltage discharge waveform (1 division down from the center). Histogram data can be seen on the top half of the display. The initial pulses from each burst result in the far right histogram (~1.8 divisions right of center). Histogram spikes to the left of that correspond to rep-rates of 100 Hz, 1 kHz, 2 kHz, 4 kHz, and 6 kHz, respectively. One can see that as the rep-rate increases, the SSPPM delay reduces by ~50 ns.

After modifications were made to the trigger circuit design, measurements showed that the relative timing jitter between the overall MO and PA SSPPMs could be less than ~10 ns under all expected operating conditions.

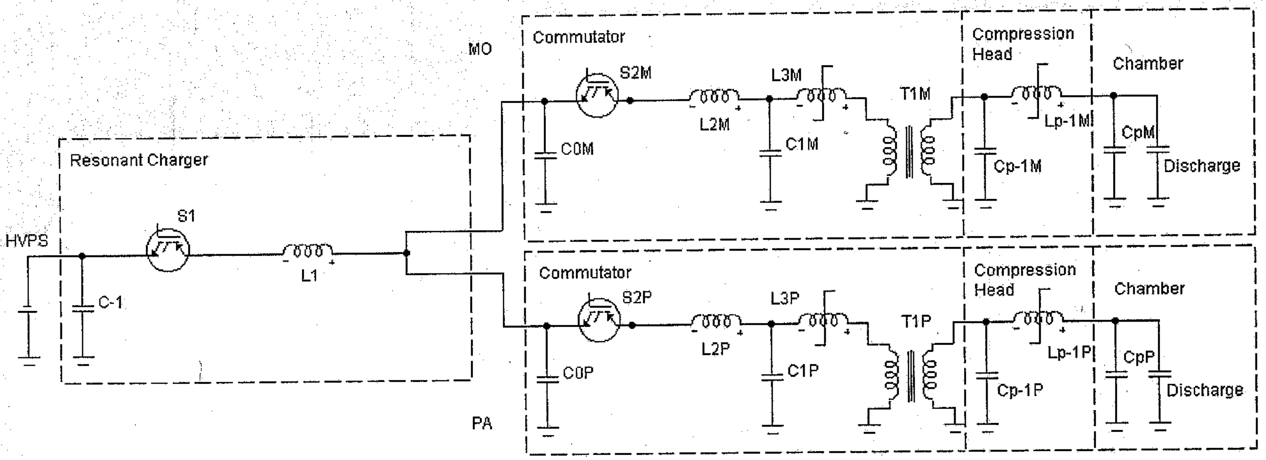

Figure 1. Schematic Diagram of MO and PA SSPPM Modules with Common HVPS and Resonant Charger.

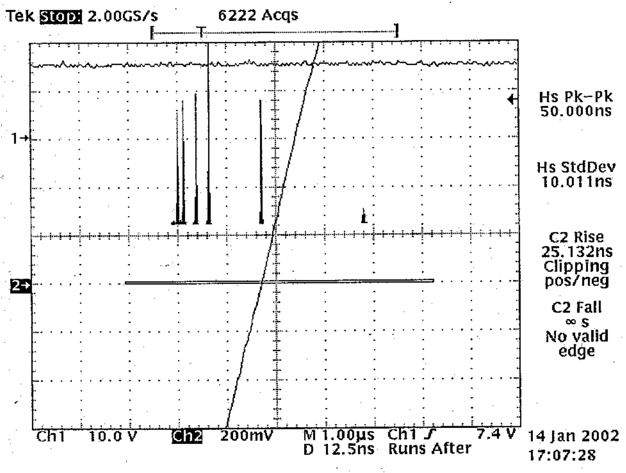

Figure 2. Timing Histogram Showing Reduction in SSPPM Delay as a Function of Increasing Rep-Rate.

Figure 3 shows the timing jitter associated with just the improved trigger circuit, now under 1 ns total spread during 6 kHz burst mode operation for over 30 minutes. One can see that some variation due to the initial pulses still exists but the amount is significantly reduced.

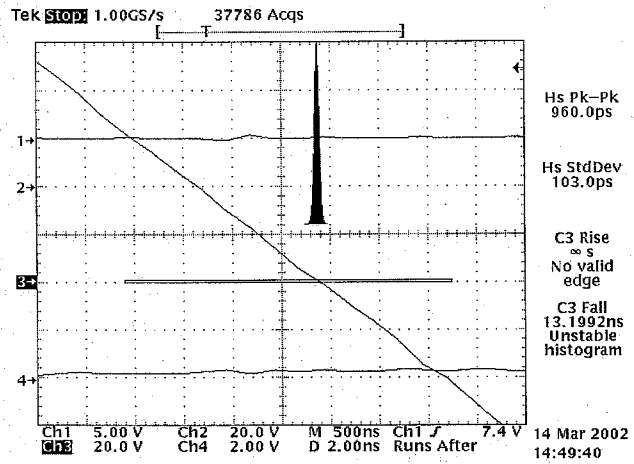

Figure 3. Timing Histogram Showing Reduced Timing Jitter of Improved IGBT Trigger Circuit.

Figure 4 shows a family of data points, representing different temperatures, showing the typical delay vs. voltage characteristics for the SSPPM. The graph also shows the data (represented by the solid lines) associated with the software model used in the controller to adjust the SSPPM timing with voltage.

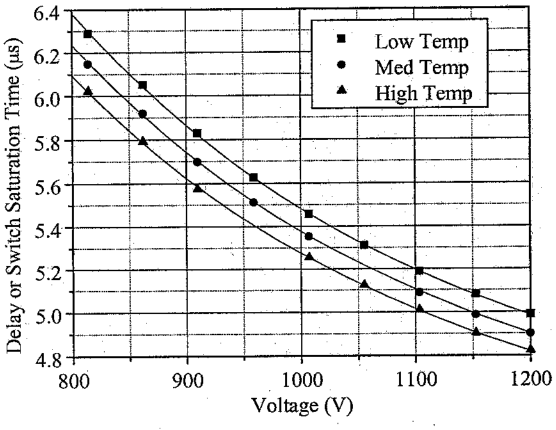

Figure 4. SSPPM Delay Vs. Voltage Data for Different L3 Magnetic Switch Temperatures.

Figure 5 shows the current MOPA relative timing performance during constant voltage, 4 kHz burst mode operation. As one can see from the data, a 10-12 ns transient exists during the first few pulses but after ~20-25 pulses, the timing reaches steady state operation and jitter less than ~5 ns peak-to-peak. Much of this transient is believed to be caused by variations in the reset of the first magnetic switch, L3. Data, shown in Figure 6, confirms how additional bias current to this switch can minimize the timing transient. In this case, the data represents the normalized timing transient of just the MO SSPPM system. Further investigations are now in progress to determine the optimum solution to improving the reset circuit operation and eliminating the transient in the MOPA timing. Work is also being conducted to research alternate magnetic materials which might be used for this switch that minimize these effects since the same bias levels currently used would drive the switch further into negative saturation where variations in bias would produce smaller delay fluctuations.

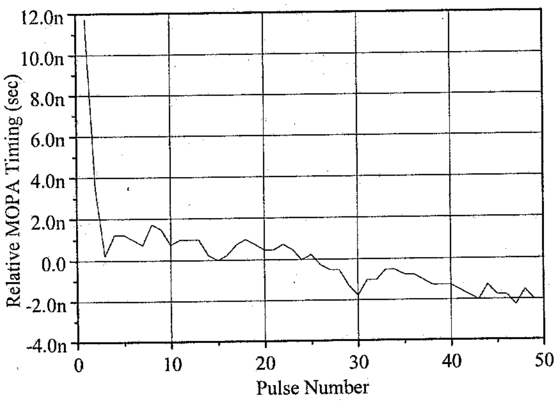

Figure 5. Relative MO-PA Timing During Burst Mode Operation Showing Transient Behavior.

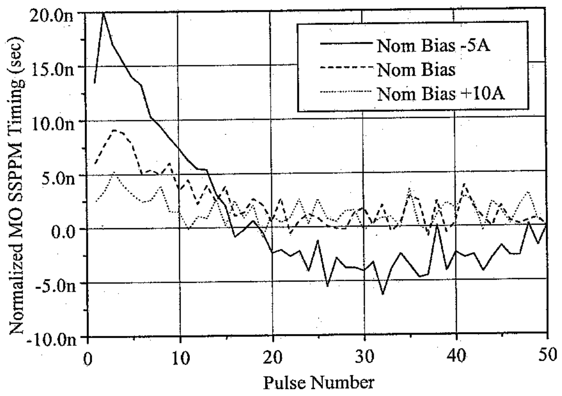

Figure 6. Normalized MO SSPPM Timing Transient Vs. Bias Current Level to the L3 Magnetic Switch.

V. CONCLUSIONS AND FUTURE DEVELOPMENT PLANS

As described earlier, the primary goal of this effort is to develop a set of two SSPPM systems that can be operated over a wide range of conditions and still maintain relative timing between the two output pulses of less than ±5 ns. Data collected to date has shown that this can be done by careful system design and by using a common charging system which eliminates the dominant effect of magnetic switch jitter, voltage variation. The primary challenges during this program have been associated with improving an IGBT trigger circuit with less than optimal timing performance and resolving other issues, likely associated with the L3 reset circuit, which are resulting in a timing transient during the first ~20 pulses of a burst. We are confident that further improvement to this circuit will result in acceptable timing for the MOPA system under all conceivable operating conditions, allowing the laser system to meet its requirements for output energy and energy stability.

VI. ACKNOWLEDGEMENTS

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VII. REFERENCES

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