A megawatt solid-state modulator for high repetition rate pulse generation

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A novel solid-state modulator capable of generating rapid consecutive power pulses is constructed to facilitate experiments on plasma interaction with high power microwave pulses. The modulator is designed to output a 100 kHz tone burst, which consists of up to 10 pulses, each with 1 μs duration and 1 MW peak power. The pulses are formed by discharging a total of 480 μF capacitors through 24 synchronized MOSFETs and 6 step-up transformers. The highly modular design, as a replacement of an old single-pulse version used in earlier experiments which employs a pulse forming network, brings great flexibility and wide potential to its application. A systematic cost-effectiveness analysis is also presented. © 2016 AIP Publishing LLC.

I. INTRODUCTION

An early series of experiments performed at Large Plasma Device (LaPD) has demonstrated the generation of broadband shear Alfvén waves (f < fci, where fci is the ion cyclotron frequency) through the interaction of a short high power microwave pulse (τ = 0.5 μs, f = fpe, where fpe is the electron plasma frequency) with a magnetized plasma. The experimental result has potential application in terrestrial radio communications by low frequency waves, as it brought new possibility for launching VLF/ELF waves (Very Low Frequency/Extremely Low Frequency) using ground-based structures, which has long been a formidable task due to their enormous wavelengths (1–100 Rearth in vacuum). To further explore ways to control the frequency of the shear Alfvén wave, the experiment was upgraded recently with the capability of modulating the microwave power injected to the plasma.

A pulse forming network (PFN) switched by a thyatron tube was used in the early experiments, which delivered a 200 kW, 0.5 μs (or 2.5 μs) duration pulse at a repetition rate of 1 Hz to energize a magnetron. This is a common type of pulse power generation scheme largely developed during the Second World War for military radars, and is widely used today for pulse power application such as fusion research, particle accelerators, and laser technology. However, the scheme usually has low repetition rates due to the time required to recover the switch. Solid-state switches can overcome this limit and offer greater flexibility in pulse width and repetition rate. A novel solid-state modulator is custom designed and fabricated to meet the special requirement of a continuously variable pulse repetition rate around ~100 kHz range for this plasma physics experiment. The modulator presented in this paper outputs a pulse train that consists of up to ten 1-μs pulses modulated up to 100 kHz, each with up to 1 MW peak power. Designs of stacked semiconductor switches have been developed in many other works but to the authors’ knowledge no pulse generator at this modulation frequency/peak power range has been described in the literature before. The highly modular design also makes it suitable for a wide variety of applications. In this article, we report the detailed design and testing results of the modulator.

II. CIRCUIT OPERATION PRINCIPLE

The modulator is composed of six identical modules with their outputs connected in series, as shown in Fig. 1(a). Each module is capable of output pulses with peak voltage of 1.2 kV and peak current of 140 A. The optimum load for the modulator is 50 Ω, which is in the operating range of the magnetron load (in this case the input side of an oil-filled 1:4 step-up transformer driving a Magnetron Type 8896). To prevent damage from arcing in the load, an over-current protection circuit is installed to monitor the total output current and cut-off the enabling gate signal in case of an over-current event.

A schematic for one of the 6 identical pulsing modules is shown in Fig. 1(b). The module is constructed around a centerpiece pulse transformer (Fig. 2). The copper housing of the ferrite cores, constructed from sections of a 5 in. copper pipe as the outer conductor, a 2 in. copper pipe as the inner conductor, and machined copper transition pieces, serves as the primary coil of the transformer, with the secondary being 3 turns of AWG 16 Teflon insulated wire, further insulated by Tygon PVC tubing. The step-up transformer generates a high voltage output while allowing a large portion of the circuit, such as the solid-state switches and the energy storage, to operate at a relatively low voltage, which greatly reduces cost for circuit components and safety protection measures. The magnetization inductance of the primary coil is estimated to be about 40 μH, which requires only about 12 A of magnetization current in the ferrite core when pulsing 500 V during 1 μs. The high current in the primary is driven by four identical pulsing circuits (described in detail below) operating in parallel. Due to the large current switched in a short period of time, parasitic inductance in the circuit must be well controlled. Fig. 2(a) is a photograph of one pulse module, and a cross-sectional sketch is shown in Fig. 2(b). The 4 pulser-boards are directly mounted on the transformer’s copper housing, which provides a solid rf ground. The MOSFETs in the circuits are mounted on the high voltage side of the primary, which also serves as their heat sink. Due to a low operating duty cycle, no additional active cooling is required.

By including a dedicated gate driver circuit, the modules are independent from each other, and can be easily reconfigured for a different application if necessary. Synchronization...
FIG. 1. (a) A schematic overview of the modulator, which is composed of 6 identical modules (M<sub>1</sub>–M<sub>6</sub>) with their outputs connected in series. The output current is monitored by a transformer and fed to an over current protection (o.c.p) circuit. (b) Diagram of a pulser module. Each module consists of a step-up pulse transformer (T), four pulsing circuit boards (B<sub>1</sub>–B<sub>4</sub>) as well as a dedicated gate driver circuit.

FIG. 2. (a) Photograph of one of the six pulser modules on a test bench. (b) A cross-sectional sketch of the pulse transformer. Note that the MOSFETs are mounted directly on the copper primary, which also serves as a heat sink.

of the gate signals is critical for the equal partition of current between the 4 pulsing boards. Attention has been given to ensure identical propagation delays. We have chosen to use a fast MOSFET driver chip (IXDD630) and a high speed CMOS opto-coupler (HCPL-7723) to minimize the turn-on jitter of the MOSFETs. The measured gate signal jitter times are less than 10 ns across all 24 paths in the modulator (Fig. 3). To protect the individual gate driver circuits from differential pickup induced by the large switching transients of the modulator output, they are placed in a rf shielded compartment in the modulator cabinet, separated from the compartment containing the high power portion of the modulator consisting of the transistors, pulse transformers, and output connections. The six modules can be easily reconnected in series-parallel configurations to accommodate different load impedances ranging from 1.5 Ω to 50 Ω. In addition, the transformer housing is designed for easy reconfiguration of the secondary windings (1–8 turns), which further expands the range of optimum output impedance (0.2 Ω – 360 Ω). In the present application, all of the six (3-turn) secondaries are connected in series.

The pulsing boards (B1–B4 in Fig. 1(b)) are visible on the outskirts of the transformer in Fig. 2. They are the building blocks of the modulator. The circuit diagram of each of these boards is shown in Fig. 4. The circuit operates in three phases: (1) charging, (2) pulse turn-on, (3) pulse turn-off, as shown in Figs. 4(b)-4(d), respectively. During the charging phase, two identical 20 µF capacitors C<sub>1</sub> and C<sub>2</sub> are charged by a 600 V 1 A dc supply. The output of the circuit is connected to the primary of the pulse transformer, and can be considered as dc short during the slow charging phase. In the presence of a high gate signal input, the MOSFET (SCT2080KE) turns on and C<sub>1</sub> discharges to generate an output pulse. A Zener diode Z protects the delicate gate-source junction from over voltage, while a bleeding resistor R<sub>4</sub> removes any residual charge on the junction when the gate driver is not connected. After the gate signal goes low, the current flowing in the primary leakage inductance can generate a large voltage transient. The circuit is protected by the clamp circuit consisting of D and C<sub>2</sub>. The inductive kick-back voltage forward biases D and the energy gets absorbed by the snubber capacitor C<sub>2</sub>, which serves to clamp the voltage to near the supply voltage. This waveform is discussed in more detail in the test results section below, and is shown in Fig. 7.

FIG. 3. Gate signals on the MOSFETs with no drain voltage applied. For clarity, only 5 representative traces are shown. The turn-on jitter times of the transistors are within 10 ns across all MOSFETs.

III. CHOICE OF COMPONENTS

In practice, an important factor to consider when making a design such as this is the cost-effectiveness. The highly modular nature of this pulse generation scheme leads to a large span of dimensions of circuit parameters (Table I summarizes the current design). However, the “sweet spot” is not obvious in this multi-dimensional space. Our approach is to identify...
the bottleneck properties of the different circuit components and make a design that maximizes component performance in those aspects. Here, we summarize such an analysis for the design of this modulator.

The key component specifications that we have found to be the main constraints in choosing different components are listed in Table II. Other specifications, which may not be directly related to the cost, still need to be considered are not discussed here. High frequency (>1 MHz) ferrite materials are chosen to minimize power loss to the ferrite core, which is estimated to be about 3% of the total output power. Because the modulator operates at a fairly low duty cycle (∼10⁻⁵) in the current application, temperature rise of the pulse transformer is negligible. The MOSFETs’ conduction losses and the switching losses are estimated to be about 1% and 4% of the total output pulse energy, respectively. The temperature rise of the MOSFETs is also negligible at the low duty cycle. We can roughly parse out the total cost as a function of 3 independent circuit parameters (N, P, and a). With comprehensive electronic databases for the circuit components that are available from most online vendors, we wrote a computer program to conditionally traverse the database with constraints listed in Table II. For each configuration of parameters (N, P, a), the program finds all possible combinations of components that meet the performance requirement and computes their total cost, the minimum of which is outputted as the cost for this circuit configuration. Figure 5 shows some results of such a calculation conducted with parts available in 2014.

In this optimization, we find the most cost effective configurations are in the range of N = 5 – 10 and P = 3 – 6; while with lower (N, P) numbers the cost rises mainly because of higher requirements on the component specifications; while with higher (N, P) numbers the cost rises because of the large number of units that need to be fabricated (cost of each unit becomes nearly constant due to the relaxed requirements on the electronic components). Considering the machining costs

![Circuit diagram](image)

**TABLE I.** Summary of circuit parameters.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Case value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load voltage</td>
<td>V_L</td>
</tr>
<tr>
<td>Load current</td>
<td>I_L</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>Δt</td>
</tr>
<tr>
<td>Number of modules</td>
<td>N</td>
</tr>
<tr>
<td>Number of pulsing boards per module</td>
<td>P</td>
</tr>
<tr>
<td>Transformer turns ratio</td>
<td>a</td>
</tr>
<tr>
<td>Number of ferrite cores per transformer</td>
<td>M</td>
</tr>
</tbody>
</table>

**TABLE II.** Key restrictions on choice of circuit components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>( \frac{V_L}{N} \cdot \frac{\Delta t}{A_{sat}} &lt; B_{sat} ) where ( A_{sat} ) is the effective cross-section of the ferrite core and ( B_{sat} ) is the saturation flux density</td>
</tr>
<tr>
<td>MOSFETs</td>
<td>( \frac{V_D}{N} &lt; V_{R} ) and ( \frac{I_D}{I_{p}} &lt; I_{P,pulsed} ), where ( V_{R} ) is the rated drain-source voltage and ( I_{P,pulsed} ) is the rated pulsed drain current</td>
</tr>
<tr>
<td>Diodes</td>
<td>( \frac{V_D}{N} &lt; V_F ) and ( \frac{I_D}{I_{p}} &lt; I_{F,pulsed} ), where ( V_F ) is the rated peak reverse voltage and ( I_{F,pulsed} ) is the rated pulsed forward current</td>
</tr>
<tr>
<td>Capacitors</td>
<td>( \frac{V_D}{N} &lt; C ) and ( \frac{I_D}{I_{p}} &lt; V_{i} \delta ), where ( V_i ) is the rated voltage, ( C_i ) is capacitance and ( \delta ) is the max voltage drop of the bank during a pulse</td>
</tr>
</tbody>
</table>

![Cost estimation graph](image)
FIG. 6. (a) Time traces of drain-source voltage ($V_{ds}$) measured with different resistive loads. The pulse is turned on at $t = 0$ and lasts 1 $\mu$s. In this case, the bank is charged to 20 V. (b) Peak drain-source voltage as a function of the bank voltage ($R_{Load} = 134 \Omega$).

FIG. 7. (a) Measurements of output waveforms with a 57 $\Omega$ resistive load. The output voltage is measured using a high voltage probe (Tektronix p6015, 75 MHz) across the load, and the output current trace is measured by a wideband current transformer (IPC CM-10-S). (b) Output power waveform of ten 1-$\mu$s power pulses modulated at 100 kHz.

and installation layout for this application, we have selected a design with 6 modules each accommodating 4 circuit boards.

IV. TEST RESULTS

For the safe operation of the transistors, drain-source voltages ($V_{ds}$) are closely monitored. Due to the aforementioned voltage kick-back on the primary of the pulse transformer during the turn-off phase, a reverse voltage occurs at the end of the pulse. Typical time traces of $V_{ds}$ measured with low-power operation are displayed in Fig. 6(a). With the secondary of the pulse transformer open circuit, the kick-back voltage is limited by the pre-charge voltage on the snubber capacitor ($C_2$ in Fig. 4), until the current decays to zero and the diode ($D$ in Fig. 4) turns off. The voltage continues to oscillate for a few cycles at $\sim 500$ kHz afterwards, which is caused by an estimated parasitic shunt capacitance of $\sim 2$ nF combined with the primary inductance. With a load attached, the diode turns off earlier due to the additional energy dissipation in the load, and the oscillation afterwards is heavily damped. In the case of the smallest $R_{Load}$, the current in the primary is the largest. Because the clamp path ($C_2$–$D$ in Fig. 4) has some stray inductance, the current cannot transfer instantaneously and a voltage transient still appears. However, this effect is mitigated at higher bank voltages as shown in Fig. 6(b), and thus does not cause problem at high power operation.

The modulator performance at high power was tested on a 57 $\Omega$, high-voltage, high-power resistive load. Fig. 7(a) shows the measured output waveforms across the load for a 1-$\mu$s pulse. The pulse rise time is estimated to be about 70 ns for the first 250 ns, which is consistent with an estimated 4 $\mu$H leakage inductance from the transformer winding. An example of output waveform of consecutive-pulses operation is shown in Fig. 7(b). A slight power droop (about 5%) shows up over the duration of the 10 pulses, mainly caused by the limited bank capacitance and the residual magnetization of the ferrite core. We estimate that the modulator can be modified with the addition of 5000 $\mu$F capacitance (rated for 600 V) to enable output of 100 1-$\mu$s pulses modulated at 100 kHz (i.e., a total duration of 1 ms), without significant total power deposition and rise of equilibrium temperature in the circuit and the pulse transformers. The transient rise of the MOSFET junction temperature is estimated to be about 40 $^\circ$C at the end of the 100 pulses, which must be taken into account with any further increase in number of output pulses.

V. CONCLUSIONS

A novel solid-state modulator is designed and fabricated to energize a magnetron for experiments of shear Alfvén wave generation by modulated microwave heating. A cost-effective design that comprises of 24 MOSFETs and 6 step-up transformers is proposed to meet requirements with the load magnetron. The independent modular design also allows easy reconfiguration to accommodate different load impedances, which brings great flexibility to its potential application. The modulator has been tested with a 57 $\Omega$ resistive load to output a burst of ten 1-$\mu$s pulse duration, 1-MW peak power pulses modulated at 100 kHz.

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