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Most Compact Pulse Power Supply for Narrowband High-Power Microband Systems

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The most compact pulse power system is one in which the functions of energy storage, voltage scaling, and pulse shaping are conducted in the same unit. A stacked Blumlein line (SBL) system addresses these functions in the same volume such that the energy density approaches the density of the energy storage dielectric. The critical elements in an SBL are the stage switches, which must close with precise timing, have inherently low inductance and rapid resistance transition time, and handle the required voltage and current. The newly developed OptiSwitch units are capable of enabling a microsecond 500-kV–1-MV pulse power unit to be constructed with pulse rates of up to several kilohertz. Since volume and mass are important parameters, the energy storage transmission lines are the major portion of the system volume when optical fiber coupled, OptiSwitch devices are employed. Higher permittivity ceramic capacitors are used to reduce the volume of the system and the length of the transmission lines required. A point design of an OptiSwitch-ed SBL system, including system volume and system performance parameters of SBL using high-energy-density capacitors with associated trigger and charging systems, is described.

KEYWORDS: Blumlein line, Compact, Low inductance, Pulse power, SiC switches

1. Background

Several high-power microwave (HPM) systems require a relatively long ($\sim 1\ \mu s$), high-voltage ($\sim$0.5–1.0 MV) pulse to drive a narrowband source with an impedance on the order of 40 Ω. The operations scenario requires a pulse repetition rate of several hertz to several hundred hertz, depending on the application. In designing a pulse power source for this application from the ground up, the objective is to minimize the volume and weight of the system. The absolute most compact system volume is the volume of the dielectric employed to store the energy in a single pulse.

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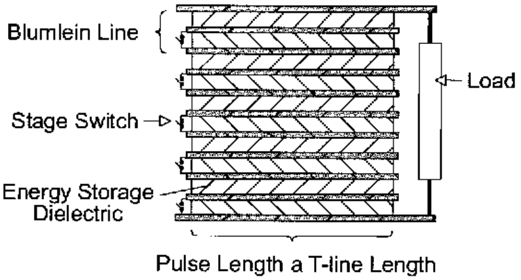

Fig. 1. Stacked Blumlein pulse generator.

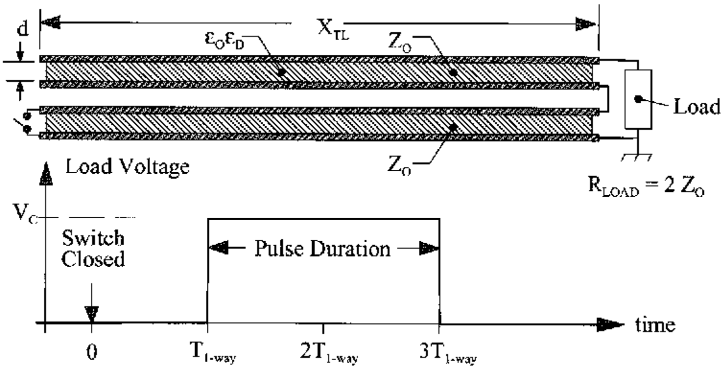

Fig. 2. Basic Blumlein operation.

The required pulse power system has several functions, including storing the pulse energy, scaling the input voltage from 10–40 kV to the required load voltage, and shaping the pulse into a square voltage-current product pulse with the required pulse duration. All three functions can be accomplished in the same structure in a stacked Blumlein line (SBL) pulse generation system illustrated in Fig. 1. The basic module of the SBL is a single Blumlein line, consisting of two transmission line sections and a switch, as illustrated in Fig 2. The single Blumlein, when connected to a load that is equal to the sum of the two transmission line sections, charged to V_C, and the ideal switch is closed, generates a square pulse in the load with a period equal to the two-way transit time of a transmission line section with an amplitude equal to the charge voltage, as illustrated by the waveform of Fig. 2. Therefore, the length of the transmission line sections, X_{TL}, and the relative dielectric constant of the transmission line dielectric, ε_D, determines the pulse length. The thickness of the dielectric, d, is determined by the dielectric strength and the charge voltage, and the width of the transmission line determines the impedance of the transmission line, Z_O. The energy delivered to the load is equal to the energy stored in the dielectric divided by the fraction of the volume occupied by the transmission line conductors,[1] neglecting the volume associated with the switches and the switch control system. Therefore, the volume of the SBL approaches the absolute minimum system volume of the energy storage dielectric, which is the most compact system possible. The density of energy storage in a real system can be about 25–33% of the maximum possible, the energy stored in the dielectric[1] when the auxiliary systems are included.

The most interesting feature of SBL systems is that a module consisting of a single Blumlein line can be used in series-parallel combinations to obtain nearly any desired output, if the switches can be precisely controlled and closed simultaneously. For example, multiple single Blumlein modules can be stacked to obtain the desired pulse voltage and/or paralleled to obtain the desired current.

The most critical components in a compact SBL are the switches, which must have very low inductive time constants and low resistive transition times. The closure time of the switches T_{SW} depends on the resistive transition time, which is a function of the switch physics, and the inductance of the switches, which is a function of the current flow geometry. Specifically, the switch closure time is given by the least-squares approach:

$$T_{SW} = \sqrt{T_R^2 + T_L^2}, \tag{1}$$

where T_R is the resistive transition time constant and T_L is the inductive time constant. The inductive time constant is given by

$$T_L = \frac{L_{SW}}{Z_O}, \tag{2}$$

where L_{SW} is the switch inductance and Z_O is the impedance of the switched transmission line. Both the switch inductance and the switch resistive transition are functions of the switch physics and thus geometrical current flow. When switching a flat-plate-conductor transmission line, as in Fig. 3, the inductance is determined by the dimensions. Assuming that the switch current is made to flow uniformly around the loop shown, the inductance is

$$L_{SW} = \frac{\mu_O \cdot x \cdot d}{w}. \tag{3}$$

To minimize the inductive time constant, the dimensions d and x are to be minimized and the width of conduction w increased to the maximum in the ideal case.

The resistive transition time constant is dependent on the switch physics during closure. The majority of switches induce conduction by changing the switch medium, normally an insulator, to a conductor. For example, a gas spark gap is closed by initiating a streamer that transitions into an arc. However, the geometrical conduction at one point across the width results in excessive inductance and thus excessive inductive time constant. In fact, most switches cannot control the location of conduction and the rate of resistance transition.

The recent advent of OptiSwitch Technology Corporation light-activated thyristors[2] has enabled the development of low impedance Blumlein modules and SBLs. The innovative OptiSwitch unit, illustrated in Fig. 4, initiates closure along a linear path, and the precise

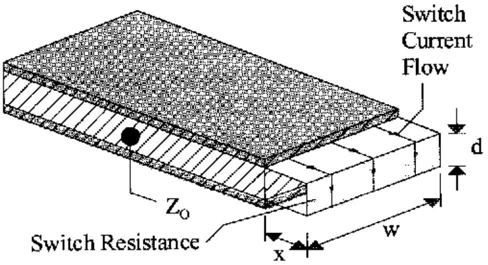

Fig. 3. Switch inductance geometry.

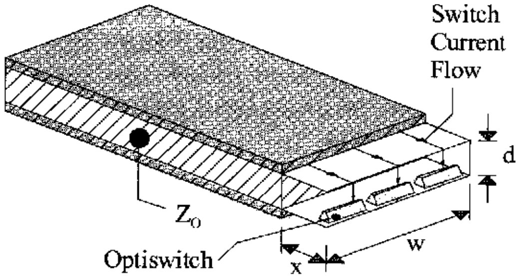

Fig. 4. OptiSwitch-ed transmission line.

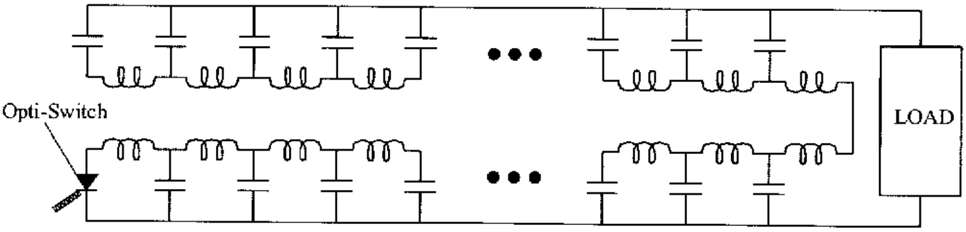

Fig. 5. Lumped element transmission line.

optical control permits multiple OptiSwitch units to be closed simultaneously. Multiple OptiSwitch units are employed, as illustrated in Fig. 4, to reduce the inductance. The resistive transition time, controlled by the quantity of optical energy injected via optical fibers, can be as low as tens of nanoseconds.

The diagrams of Blumlein lines illustrated in the preceding figures are distributed transmission lines with the wave transit time controlled by the relative dielectric constant so that the pulse length is given by

$$T_P = \frac{2 \cdot X_{\mathrm{TL}} \cdot \sqrt{\varepsilon_R}}{c_O}, \tag{4}$$

where c_O is the free space light speed.

To reduce the length of the transmission line sections for long pulses, the relative dielectric constant can be increased to several thousands and a lumped element transmission line fabricated, as illustrated in Fig. 5. The individual capacitors and inductors are designed to provide a resonant frequency that is compatible with the desired rise time.

The near-term approach is to use commercially available capacitors and fabricate a lumped element transmission line, as shown in Fig. 6. The number of capacitors, the capacitor value, and capacitor spacing between conductors can be arranged to provide the desired impedance and the desired pulse length. Note that commercially available capacitors are not fabricated with high energy density as a goal. However, specially designed capacitors with high permittivity and minimum enclosure material will result in a very compact system.

The stack of Blumleins is charged from the stage closest to ground, with isolating inductors or diode strings between each stage, as illustrated in Fig. 7. When inductors are used in the charging circuit, the resultant charging circuit is a slow wave system and the inductors are designed such that the charging time is much greater than the Blumlein line transit time. The inductors in parallel with the transmission line sections produce an inductive decay on

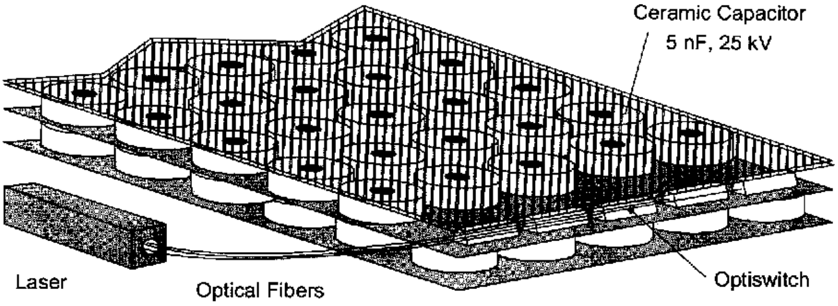

Fig. 6. OptiSwitch lumped element Blumlein line.

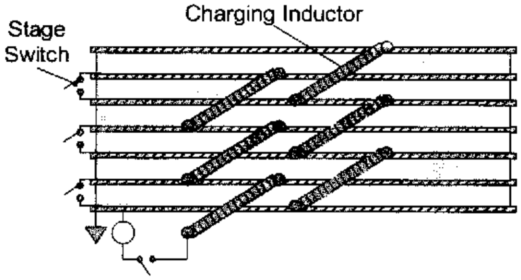

Fig. 7. Charging inductor or diode stack.

the output pulse. For pulses of longer duration, diode chains are more efficient in charging the stacked Blumlein because the charging time can be much closer to the pulse discharge time and the output pulse is delivered to the load with minimal droop.

2. Description of OptiSwitch Operation

The key, new technology that makes this application and SBL applications possible is the OptiSwitch, also shown in Fig. 6, that can be closed very precisely in time to distribute the current uniformly across the transmission line to reduce the inductance. The closure rate or resistive transition time of an OptiSwitch is proportional to the peak optical power delivered to the switch via optical fibers.

The OptiSwitch, light-activated thyristors are based on an asymmetrical design that is processed by OptiSwitch in a 4-in. wafer fab. This limits the usable length of a linear switch to approximately 5 cm. The absorption depth of the Nd:YAG laser limits the depth of the switch to ~2 mm, giving a total area of 1 cm^2 per switch.

Figure 8 shows the anode voltage and the anode current of the 12.5-kV thyristor when the switch is activated with a 5-ns light pulse. The laser light energy is 4.3, 8.5, and 13 mJ. The shaded area defines the operating voltage drop at 50 ns, which is the point of maximum power dissipation. This is the energy for five switches, enough for one Blumlein. For slow resistive transition times (~1 μs), solid-state lasers can provide sufficient optical peak power to close the switch on that time scale. In the short-pulse SBL or single Blumlein module application, which require the resistive transition time to be on the order of tens of nanoseconds, a high-power, solid-state laser similar to a Nd:YAG system is required.

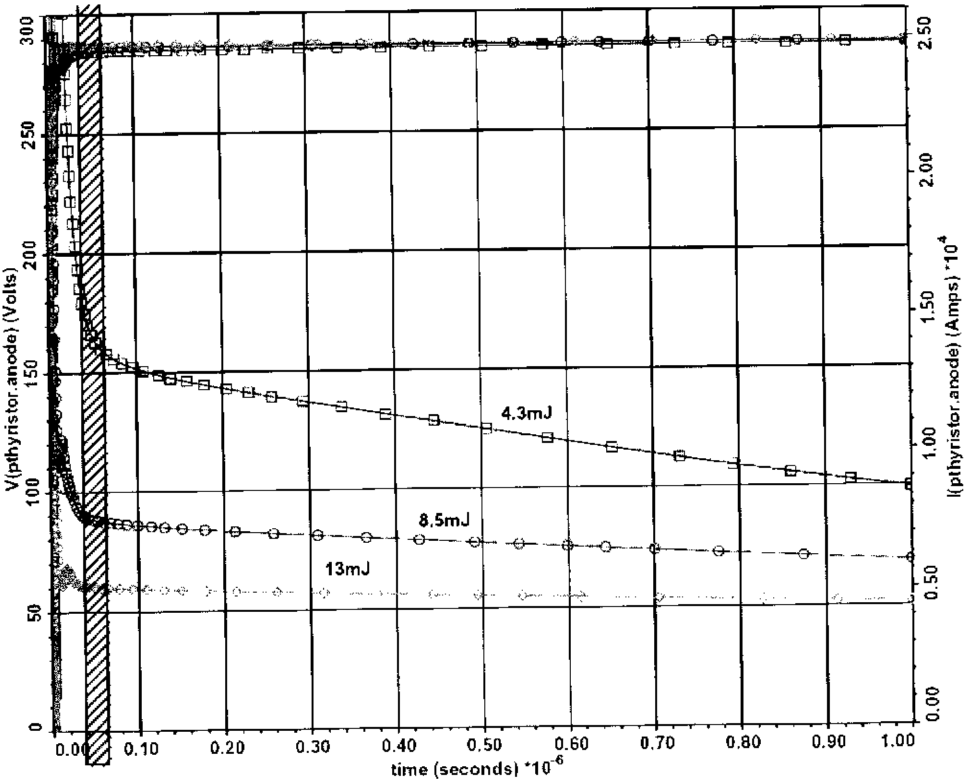

Fig. 8. Anode voltage and current for a 12.5-kV-thyristor-based switch.

Nd:YAG systems, now manufactured with semiconductor laser diode pump systems, can operate at kilohertz pulse rates and are quite compact, reliable, and long lived. The addition of the laser reduces the total energy density of the system to about half that of the dielectric, if the dielectric is stressed near the maximum values.[1]

For this application five switches are required to switch each Blumlein. A switching simulation was performed using Medici, which is an advanced two-dimensional semiconductor simulation package. A 12.5-kV switch with an area of 5 cm^2 (five 1-cm^2 switches in parallel) and a 25-kV switch, also of 5 cm^2, were simulated and compared for energy dissipation. For the Blumlein cases in this paper, the number of OptiSwitch units represents a total of 200 or 100 switches, respectively (40 or 20 stacked Blumleins). The simulations were done to keep the total optical energy constant between the two cases. The switch voltage versus time simulation, shown in Fig. 9, indicates that the closure time of the switches in a 20 Blumlein line stack with 5 parallel switches per Blumlein line is approximately 30 ns. In the figure the optical energy is 8.6, 17, and 26 mJ, respectively. Again, this is the energy sufficient for five switches, enough for one Blumlein, and it is double the energy for the 12.5-kV case.

Note that the strength of the optically triggered switches in this application is the capability of very low switch-to-switch-closure time jitter. The arrival of the optical energy determines the start of switch closure such that the closure time jitter is a small fraction of the optical pulse length of 10–20 ns.

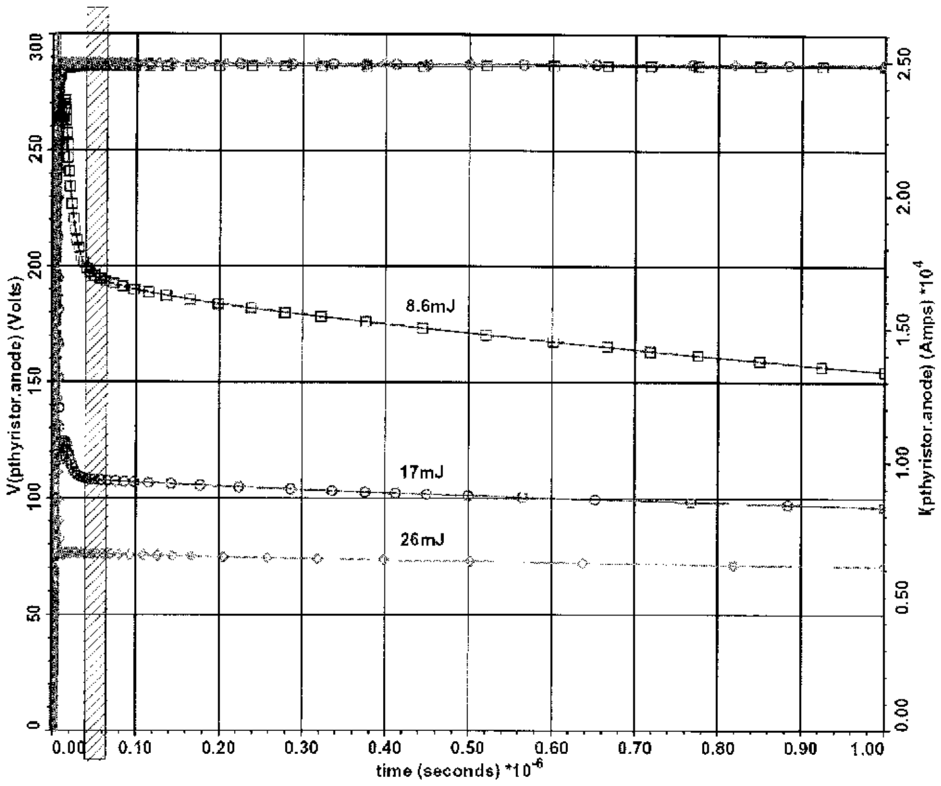

Fig. 9. Anode voltage and current for a 25-kV-thyristor-based switch.

3. Point Design of OptiSwitch SBL HPM Pulse Source

The SBL approach is most applicable to the design of a narrowband HPM pulse power system with the parameters listed in the first part of Table 1. The charge voltage of the individual Blumlein lines is determined by the OptiSwitch voltage, which has been demonstrated at 25 kV. The number of Blumleins in the stack is determined by the load voltage divided by the charge voltage. The load voltage and current requirements determine the output impedance of the SBL. The load pulse length determines the total energy storage capacitance at the charge voltage and the commercially available capacitor values and dimensions.

The specific component design and transmission line design for the point SBL design are defined in Table 2. Note that the conventional capacitor energy density in this case is about a factor of 25 less than the currently available, maximum energy density of ceramic capacitors of about 1 J/cm^3. Therefore, the designs in Table 2 serve only to define representative SBL systems using conventional capacitors and high-energy capacitors, which reduces the volume of the SBL by at least an order of magnitude. Also note that the high-energy-density design employs a higher charge voltage switch, which has been demonstrated by OptiSwitch in limited production.

The required OptiSwitch laser closure energy parameters are listed in Table 3, which compares the OptiSwitch parameters for two cases for the middle energy level (8.5 and

Table 1. SBL system parameters

Parameter	Symbol	Conventional capacitor design	High-energy-density capacitors	Unit
Load				
Voltage	V_L	$5.00E{+}05$	$5.00E{+}05$	V
Impedance	Z_L	40.00	40.00	Ω
Current	I_L	$1.25E{+}04$	$1.25E{+}04$	A
Pulse duration	T_P	$1.00E{-}06$	$1.00E{-}06$	s
Pulse energy	E_L	$6.25E{+}03$	$6.25E{+}03$	J
Blumlein				
Charge voltage	V_c	$1.25E{+}04$	$2.50E{+}04$	V
Number of SBLs	N_{bl}	40	20	
SBL impedance	Z_{sbl}	40	40	Ω
Blumlein impedance	Z_{bl}	1.00	2.00	Ω
T-line impedance	Z_{tl}	0.50	1.00	Ω
Switch voltage	V_{sw}	$1.25E{+}04$	$2.50E{+}04$	V
Switch current	I_{sw}	$2.50E{+}04$	$2.50E{+}04$	A
Stacked Blumlein dimensions				
Conductor thickness	t_c	$1.00E{-}03$	$1.00E{-}03$	m
Single Blumlein height	h_{bl}	$2.30E{-}02$	$1.30E{-}02$	m
Total SBL height	h_{sbl}	$8.81E{-}01$	$2.41E{-}01$	m
SBL length	l_{sbl}	$1.05E{+}00$	$1.65E{+}00$	m
Blumlein width	w_{bl}	0.25	0.05	m
Total number of capacitors	N_c	8,000	1,280	
System				
Single Blumlein energy	E_{bl}	$1.56E{+}02$	$3.13E{+}02$	J
Stacked Blumlein energy	E_{sbl}	$6.25E{+}03$	$6.25E{+}03$	J
Stacked Blumlein width	w_{sbl}	25	5	cm
Stacked Blumlein height	h_{sbl}	92	26	cm
Stacked Blumlein length	l_{sbl}	105	165	cm
Stacked Blumlein volume	$\mathrm{Vol}_{\mathrm{sbl}}$	0.23	0.02	m^3
SBL energy density	$E_{d\text{-sbl}}$	$2.70E{+}04$	$3.14E{+}05$	$\mathrm{J/m}^3$
		0.03	0.31	$\mathrm{J/m}^3$

17 mJ). At this optical energy level, the 25-kV case is preferred, as the voltage drop is not double for the same total light energy. Thus the total system dissipation is less. For the 25-kV case the total switch dissipation is 520 W at 10 Hz compared to 784 W at 10 Hz for the 12.5-kV simulation. For the 8.5/17-mJ case the total light energy is 340 mJ. Using a conservative coupling efficiency of 50% yields a total light energy of 680 mJ or 6.8 W of average light power. This light energy is readily available from commercial Q-switched lasers, which can generate joules of energy in 5–10-ns pulses at a 100-Hz rate. The power dissipated in the switch and that required by the laser should be compared to 62.5 kW of generated electrical power. Even with a poor laser efficiency of 10%, the laser power is at the noise level for the overall system.

Table 2. SBL component parameters

Parameter	Symbol	Conventional capacitor design	High-energy-density capacitors	Unit
Capacitor design				
Value	C	1.00E−08	1.56E−08	F
Voltage	V	2.50E+04	2.50E+04	V
Diameter	d_c	0.050	0.050	m
Height	h_c	0.010	0.005	m
Energy	E_c	7.81E−01	4.88E+00	J
Volume	v_c	1.96E−05	9.81E−06	m^3
Energy density	ed_C	3.98E+04	4.98E+05	J/m^3
		0.04	0.50	J/cm^3
T-line design				
Total capacitance	C_t	1.00E−06	5.00E−07	F
Conductor width	w_{tl}	0.250	0.050	m
Number of sections	N_{tl}	20	32	
Capacitor separation	d_{cs}	5.00E−02	5.00E−02	m
Section capacitance	C_s	5.00E−08	1.56E−08	F
Number of capacitors/section	N_s	5	1	
Total inductance	L_t	2.50E−07	5.00E−07	H
Section inductance	L_s	1.25E−08	1.56E−08	H

Table 3. SBL OptiSwitch parameters

Parameter	Symbol	Design 1	Design 2	Unit
Blumlein switch				
Switch blocking voltage	V_{sw}	1.25E+04	2.50E+04	V
Switch current	I_{bl}	2.50E+04	2.50E+04	A
Switch closure time (95%)	T_{sw}	<5.00E−08	<5.00E−08	s
Pulse repetition rate	P_{rr}	1.00E+01	1.00E+01	Hz
OptiSwitch				
Switch blocking voltage	V_{sw}	1.25E+04	2.50E+04	V
Switch current	I_{sw}	2.50E+04	2.50E+04	A
Number of switches/Blumlein	$N_{s/b}$	5	5	
Optical energy/switch/pulse	$E_{o\text{-sw}}$	3.4	6.8	mJ
Total optical energy/Blumlein/pulse	$E_{o\text{-sw-}t}$	680	680	mJ
Average optical power/Blumlein	$P_{o\text{-avg}}$	6.8	6.8	W
Switch current pulse duration	T_P	1.00E−06	1.00E−06	s
Switching dissipation/switch	$P_{s\text{-cond}}$	3.9	5.2	W
Total switch dissipation	$P_{st\text{-cond}}$	780	520	W

4. Conclusions

The application of the newly demonstrated OptiSwitch high-voltage, light-activated thyristors in a high-energy-density stacked Blumlein line configuration makes possible the most compact pulse power system for narrowband high-power microwave systems. The unique features of the OptiSwitch devices are the high voltage ratings, the capability to close very rapidly owing to the use of a high-power-laser trigger, and the ability to distribute the current over a wide distance to reduce the inductance. These features can be employed using conventional low-energy-density ceramic capacitors in lumped element transmission line sections. The use of higher-energy-density capacitors (one half of the maximum demonstrated values) can reduce the volume of the system by an order of magnitude to a system that is 5 cm wide × 26 cm wide × 165 cm long and an SBL energy density of 0.3 J/cm^3.

The auxiliary issues of optical control energy sources and thermal management are being developed to enable fielding a complete system at a higher pulse rate. The thermal management issue is easily manageable for 10 Hz, and nominal active cooling is sufficient for 100-Hz operation. Development of the higher voltage OptiSwitch devices is also being pursued under other government contracts.

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The Authors

Dr. David Giorgi received his B.S., M.S., and Ph.D. in electrical engineering (applied physics) from the University of California at San Diego. After finishing his undergraduate studies he began his career at the Energy Compression Research Corporation (ECR) in 1984. At ECR he worked in the field of magnetic energy storage and switching, fast risetime (<100 ps) high-power (multimegawatt) light-activated switches, high-speed Pockels Cell drivers, and actively Q-switch microlasers. At ECR he was on the team that demonstrated high-efficiency (47.5%) energy transfer from two uncoupled inductors. He also demonstrated extremely high dI/dt switching of $\sim 10^{15}$ A/s using a light-activated switch in a low-impedance circuit. He is currently the President and CEO of OptiSwitch Technology Corporation, which he founded in 1999. At OptiSwitch his main focus is on high-power solid-state switches for pulsed power applications, high-power electronics, and optical control of power semiconductors. Dr. Giorgi has authored numerous papers in the area of light-activated switching and has coauthored three patents.

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Dr. Robert M. O'Connell received the B.E. degree in electrical engineering from Manhattan College, New York, in 1971 and the M.S. and Ph.D. degrees in electrical engineering from the University of Illinois, Urbana, in 1972 and 1975, respectively. From 1975 to 1979 he was an officer in the U.S. Air Force, where he served as a Research Electronics Engineer. In 1978 he was awarded the USAF Research and Development Award for contributions to piezoelectric materials for RF and microwave components for radar applications. In 1980 he joined the University of Missouri, where he is currently Professor of Electrical Engineering. He has held temporary positions at the F.J. Seiler Research Laboratory, the Jet Propulsion Laboratory, the Air Force Weapons Laboratory, the Naval Weapons Center, the Rome Air Development Center, and NASA Glenn Research Center. He has conducted research and published articles on piezoelectric materials for microwave and radar components, optical materials for high-power laser systems, optoelectronic microwave power amplifiers, power electronics, power systems, and applications of linear electric motors. He is a Senior Member of the IEEE and a registered Professional Engineer.