ACTIVE RF PULSE COMPRESSION USING ELECTRICALLY CONTROLLED SEMICONDUCTOR SWITCHES

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Abstract

In this paper, we will present our recent results on the research of the ultra-fast high power RF switches based on silicon. We have developed a switch module at X-band which can use a silicon window as the switch. The switching is realized by generation of carriers in the bulk silicon. The carriers can be generated electrically or/and optically. The electrically controlled switches use PIN diodes to inject carrier. We have built the PIN diode switches at X-band, with <300ns switching time. The optically controlled switches use powerful lasers to excite carriers. By combining the laser excitation and electrical carrier generation, significant reduction in the required power of both the laser and the electrical driver is expected. High power test is under going.

HIGH POWER RF SWITCHES AND ACTIVE RF PULSE COMPRESSION

Modern high gradient normal-conducting accelerator structures are powered by very high level pulsed RF. Short pulses are desired to reduce the wall losses and the average RF power, but the efficiency of the RF tubes deteriorates at such a short pulse length. RF pulse compression systems are then commonly employed to match the longer pulses from the RF tubes with relatively lower power to the structures which require shorter but higher power pulses.

Several pulse compression schemes have been studied since the first RF pulse compression system for RF accelerator structures, SLED (SLAC Energy Doubler) [1] was invented, such as BPC (Binary Pulse Compression system) [2] and SLED II [3]. BPC has 100% intrinsic efficiency, but the overmoded waveguide assembly in the system is extremely expensive and large in size. The compact SLED II pulse compression system employs high Q resonance delay lines behind an iris to accumulate RF energy from the incoming pulse. The stored RF energy is discharged by reversing the phase of the input pulse, so the reflected pulse from the input and the emitted RF from the delay line can add together to form a higher-power pulse. SLED II is more efficient than SLED, but the efficiency deteriorates at high compression ratio. The maximum power gain for a lossless SLED II system is 9 if the phase of the RF source can be reversed; without phase flipping, the maximum power gain is only 4.

Active pulse compression systems using high power RF switches has been suggested to improve the efficiency of the resonant delay line pulse compression system [4]. In an active system, the iris between the RF input and the resonance delay line is switchable, so that the RF energy

stored in the delay lines can be fully discharged in one delay cycle. There is no intrinsic limit for maximum power gain in active compression systems, but the gain is limited by the amount of losses in the switch and the delay line. Fast switching time and high power handling capacity are also required.

In the rest of the paper, we will present the recent results of our research on the ultra-fast high power RF electrically controlled semiconductor switches. The switch utilizes an electric circuit to inject carriers into bulk silicon, so the reflection of RF is changed. This switch demonstrated fast enough speed and low enough loss for active pulse compression applications, with 8 times power gain achieved. The process for the PIN diodes is compatible with the popular CMOS IC process. The requirement of the driver for the solid state silicon switch is also lower than other options. A typical setup uses a 1kV 1kA pulsed power driver, while the plasma switches and the ferroelectric switches need about 100KV driver voltage, and the optical switch [5] requires a costly high-power laser.

THE TUNABLE SWITCH MODULE
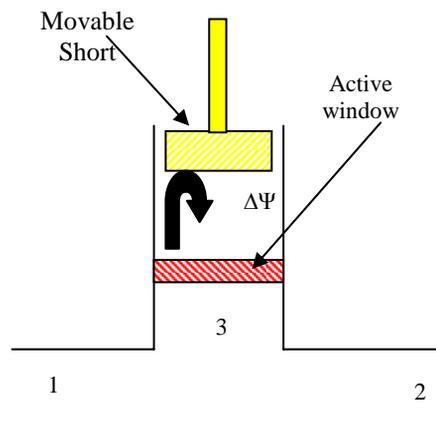
Figure 1: The tunable switch module.

The active pulse compression system requires a switchable iris with certain coupling coefficients at charging and discharging phases. The optimized coefficients are functions of many variables such as compression ratio, losses in the delay line and losses at the iris. A tunable switch module was then designed to match coupling coefficients of the active window to desirable values at both *on* and *off* states. The module is composed of a Tee junction with the active window and a movable short plane connected to the 3rd port, as shown in Fig. 1.

When the active window is turned on, it acts as a short plane and the phase of the reflected signal from the third-

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port changes. Hence, the coupling coefficients relating the remaining two ports are switched. These coefficients depend on the location of the active window, which determines the coupling in the *on* state, and the location of the movable short, which determines the coupling in the *off* state.

A low-loss circular waveguide Tee junction has been specially designed and machined for our test setup. This Tee is composed of a TE_{20} mode rectangular Tee and 3 circular-to-rectangular mode converters [7], with S_{33}=0.

PHYSICS AND DESIGN OF THE ACTIVE SILICON WINDOW
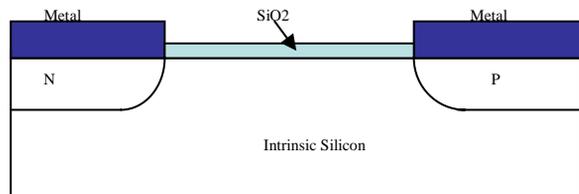
Figure 2: Cross-section of one PIN diode (not to scale).

Recently, we have designed a new active switch window working in a circular waveguide. Like the switch Tamura and Tantawi developed in [6], this switch also works under TE_{01} mode.

To demonstrate a fast switching speed, we have chosen a waveguide diameter of 1.299 inch (3.299 cm), which is very close to cutoff and results in a high Z_g of 1554Ω at 11.424GHz and less amount of carriers is required for the switching, with the cost of power handling capacity. We have chosen the planar structure PIN diodes, with both P and N doping on the front surface of the silicon window. The cross-section of the diode is shown in Fig. 2. This structure allows shorter intrinsic region length, so the carrier can be injected to center of the diode faster. There are 960 diodes in the switch, with about 70μm in width.

In our design, there is a metal ring on the window, providing positive bias for the diodes. The diodes only cover a ring between the waveguide wall and metal ring. The metal ring's width and radius is adjusted so that the window can be matched when the switch is off. This is very helpful in reducing the losses and the maximum field in the 3rd arm during the charging phase. More interesting, this ring also helps the RF reflection when the switch is on, so the required amount of injected carriers is reduced.

Simulation with HFSS shows that when the diodes are *off*, the window has 0.7% losses and 98% transmission coefficient. This assumes a 500μm thick silicon wafer with a 100KΩcm resistivity. When the diodes turn on, eventually a carrier layer with 50 μm thickness and a density of $5 \times 10^{16}/cm^3$ is formed. This layer and the metal ring result in a transmission of less than 1% and power losses of about 10%.

We have simulated the time response of the diodes with the Medici code. The dopant profiles of the devices used in Medici simulation were imported from the result of process simulation with TSupreme. The actual process was optimized based on the simulation results as well as the testing results. For planar structure diodes with 60μm length, which are connected in parallel, simulation shows that the average carrier density of the top 50 μm layer at center of the diodes will rise to $5 \times 10^{16}/cm^3$ after about 200 μC of charges injected. The length of the diodes is chosen to minimize the non-uniformity of carrier distribution. With a current source providing 1 KA pulse, the switch can be turned on in 200ns.

Figure 3: Fabricated Active Window.

We have made such a switch as shown in Fig 3. The fabrication of the switch was completed at the Stanford Nanofabrication Facility with CMOS compatible process. The switch was built on a Floatzone silicon wafer with 90K Ωcm resistivity and 500 μm thickness.

LOW POWER EXPERIMENTAL RESULTS

We have characterized these switches with both network analyzer measurements and active switching tests; we performed the tests under the one-pass setup as well as the module setup with the switch attached to the circular Tee and a movable short. After that, we tested the switch in the active pulse compression system.

In the one-pass network analyzer characterization, we have measured S_{12}=0.939 and S_{11}=0.267 with 4.7% loss, including about 2.5% losses over the mode converter and the wafer holder. Part of the losses is caused by the implanted dopant, which is not included in the HFSS simulation. The wafer holder was tested to have S_{12}=0.982. However, all the active tests were completed with an earlier version of holder, which has a larger gap, resulting in higher reflection and losses. We have also made the network analyzer measurement for the module setup, which can successfully adjust the S-matrix of both on and off state. When the module is optimized for the active compression test with phase flipping, the off state loss was measured at 4.1%. The loss can be reduced to about 3.8% with the new holder.

Active switching tests have been performed with both one-pass setup and the module setup. The switch is powered by an IGBT circuit. A <300 ns switching time and about 15% on state losses have been observed in both the one-pass setup and module setup.
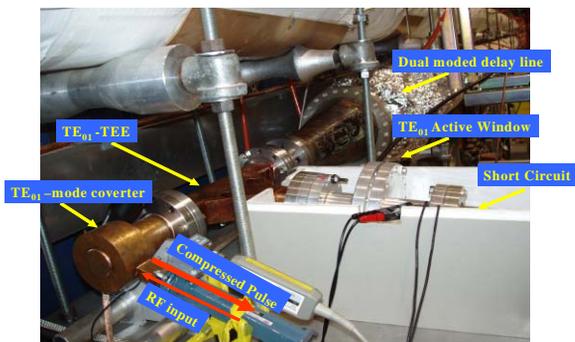
Figure 4: Active Pulse Compression Experiment Setup.
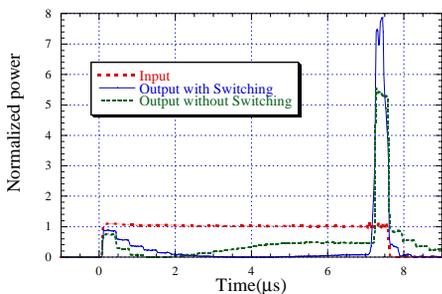
Figure 5: Active Pulse Compression Test with Input Phase flipped.
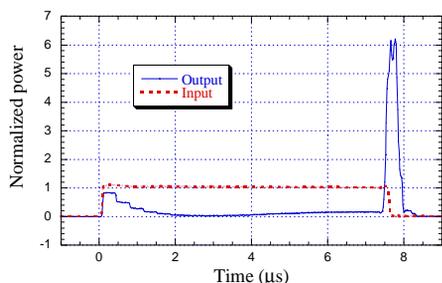
Figure 6: Active Pulse Compression Test without Input Phase flipped.

In the setup of the active pulse compression as shown in Fig. 4, port 2 of the switch module is attached to a 375ns resonant delay line, and the port 1 is connected to the RF input. The switch is driven by 700V 1400A pulses with 250ns duration. The optimized test results are shown in Fig. 5 and 6. In all the tests, input pulse width is 20 times of the output pulse width. For a system which cannot flip the phase of the RF input, the switch turns on when the input turns off. 6 times power gain has been observed, compared to a theoretical gain of 2 times for a passive compression system without phase flipping, given the losses of our delay lines. For a system which can flip the phase of the RF input, the switch turns on at the same time of the phase flip. The active system has achieved a compression gain of 8, compared with the gain of 5 achieved by the passive system using the same delay line.

FUTURE ENHANCEMENT

The power handling capacity of the switch is eventually limited by the electric break down in the silicon.

Estimated with the DC breakdown field of 30MV/m, the window with 1.299 inch diameter can handle about 120 MW of traveling wave. If two equal power waves flow from the both side of the window, the limit will be about 30 MW. The experiment of determining the actual RF breakdown electric field for the silicon wafer is still ongoing.

To enhance the power handling capacity further, we can use a RF network to distribute the power to several active elements. One option is to divide the power into several switch modules described in Fig. 1 and then combine them together. Another option is to build a switch network in Fig. 7. The RF phase from the active window to the short end is small, so the field at the window is reduced. Each module only needs a small change in the reflection coefficient after switching, so the network can multiply the change to desired value.
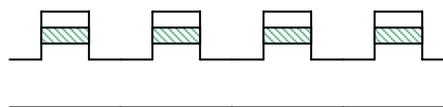
Figure. 7: A Serial Switch Network.

The switching speed can be enhanced further by increasing the carrier generation rate. One possible option is to increase the current, but the potential improvement is limited. Another possible option is to apply reverse bias on the diodes to breakdown the diode; a low power laser can be used to generate some carriers and assist the breakdown. The high power RF field can also help the generation of carriers and enhance the speed.

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