# Quasi-Optical Cavity Dumping at Millimetre Wave Frequencies

G.M.Smith, J.C.G.Lesurf, Y.Cui, M.Dunn

J.F.Allen Research Laboratories, Department of Physics and Astronomy,
St. Andrews University, Fife, Scotland

***Abstract*** - A thin silicon wafer when illuminated by a Q-switched frequency doubled Nd-YAG laser is used as a very fast, ultra-low loss, quasi-optical, photo-conductive switch to cavity dump a millimetre-wave open resonator. This novel scheme should provide short pulses at millimetre wave frequencies with power gains of several hundred from conventional cw sources. Potential applications are in high resolution radar, plasma diagnostics and pulsed electron spin resonance experiments.

## Introduction

For a millimetre wave beam at 94GHz in an open near confocal cavity, it has been demonstrated that, with beam-splitter coupling, the finesse of a matched cavity can exceed 1500, and be limited only by the resistive losses in the copper mirrors (0.1% at 94GHz)[1]. For a matched cavity this leads to a circulating power within the cavity that is about 500 times greater than the incident power density. It would be of considerable value if this power level could be cavity dumped, by switching the power out of the cavity very fast.

This requires a switch that is fast compared to the round trip time of the cavity, but does not significantly degrade the losses and circulating power within the cavity. This requires a switch to operate on nano-second or sub-nano second time scales but with an insertion loss of <0.1% power (<0.004dB).

## Quasi-Optical Switch

Such a switch has been demonstrated using a very thin sheet of high resistivity silicon placed at 45 degrees in a high Q open resonator as illustrated schematically in Figure 1. In normal operation, the silicon acts as a dielectric sheet and can have extremely low insertion loss. However, it can be switched by illuminating the sheet with above bandgap radiation from a fast rising laser pulse. This creates an almost instantaneous electron-hole plasma layer that can have metallic properties at high enough carrier densities and reflect nearly all the microwave power out of one arm of the cavity.

This occurs when the plasma frequency exceeds the rf frequency. Above this density the silicon becomes more and more reflecting. According to the Drude model the plasma also becomes more lossy until the skin depth at the rf frequency becomes comparable to the thickness of the plasma layer. At this point the plasma will be almost perfectly reflecting.

High purity silicon (resistivity > 10kohm cm) has extremely low loss at millimetre and sub-millimetre wave frequencies [2], with power absorption <0.02 $cm^{-1}$ at 100GHz and no more than 0.05 $cm^{-1}$ between 100GHz and 2THz. Thus the silicon's resistive loss can be small compared to the resistive loss in the end mirrors.

Normally the loss due to reflection from the silicon dielectric sheet would ruin the Q of the cavity. The refractive index of silicon is 3.418, which, at 45 degrees incidence, gives a reflection off a single air-silicon interface of 18% for the low reflective linear polarisation state. In initial experiments we have used a beam-splitter of thickness 130μm. At 94GHz this gives a net reflection of 42% for the low reflectivity polarisation state.

The loss due to this reflection can be cancelled by positioning a third mirror in a Michelson interferometer arrangement as illustrated in Figure 1. The tolerance on the positioning of this mirror, and spatial beam matching required, to achieve cancellation of the two beams is substantially reduced by having a low beam-splitter reflectivity. (For a thickness of 10μm the net reflectivity of the beam-splitter reduces to less than 0.5%.)

Experimental measurement of the cavity Q and coupling parameter has shown that a 130μm silicon wafer (3 inch diameter) when placed at the beam waist of a quasi-optical near confocal cavity, of length 360mm, contributed no more than 0.05% extra loss in the cavity. In this particular experiment, diffraction losses around the wafer may also have contributed significantly to this figure.

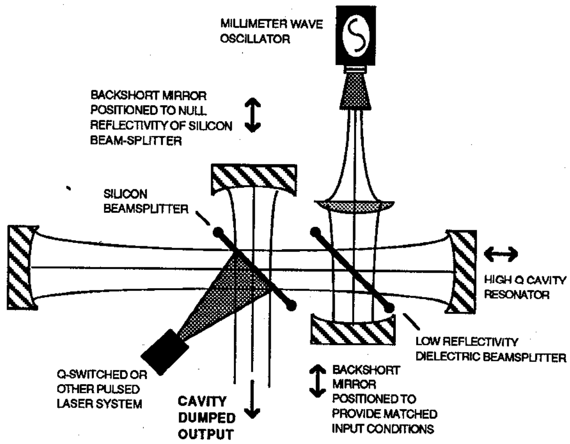


Fig. 1 Diagram illustrating the principle of quasi-optical cavity dumping. When the silicon beam-splitter is illuminated by a laser pulse it changes from a low loss dielectric to a highly reflective plasma and dumps power from one arm of the cavity.



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### Laser Requirements

Fast optical switching using silicon was first suggested by Auston who demonstrated electronic switching at rates of a few picoseconds [3]. He used single pulses from a mode-locked Nd:glass laser (and doubling in KDP) at a power level of a few micro-joules per pulse to achieve switching at 1GHz and 10GHz in micro strip [4]. The illuminated area here was of the order $1\times10^{-3}$ cm$^2$.

Switching and phase shifting has also been successfully demonstrated at 94GHz using silicon waveguide circuits on sapphire, and illuminating with diode lasers operating at 0.9µm and mode-locked frequency doubled Nd:YAG lasers[5]. Here too, the area of illumination was relatively small which allowed the use of mode-locked lasers with very short pulse durations.

The illuminated area in a quasi-optical switch is much larger than that required for microstrip or dielectric waveguides. This implies energy levels a thousand times larger and the use of a Q-switched rather than a mode-locked system. The disadvantage of a Q-switched system is that the pulse length is now typically of the order of 10ns.

The optical requirements for light activated high voltage switches have been considered in [7] where diode pumped Q-switched YAG (or YLF) lasers were shown to have considerable advantages over other potential systems in terms of efficiency and the amount of energy (number of photons) per pulse.

However, the YAG wavelength of 1.06µm is close to the bandgap of silicon and has an absorption depth of 1.4 mm which is significantly larger than the thickness of silicon. It is thus preferable to use frequency doubled Nd:YAG at 0.53µm, because the high conversion efficiencies (>60%) and low absorption depth (1.25µm) allow more photons to be absorbed in the silicon. Frequency doubling also has the advantage of tightening up the leading edge of the laser pulse.

Figure 2 models the theoretical reflectance of a 130µm silicon switch as a function of absorbed energy at 0.53µm. This is a very simple model in that it treats the plasma region as a uniform 1.25µm layer and assumes that recombination and diffusion times are negligible compared to the switching time. Nevertheless, it serves to illustrate the amount of laser energy required for effective beam switching.

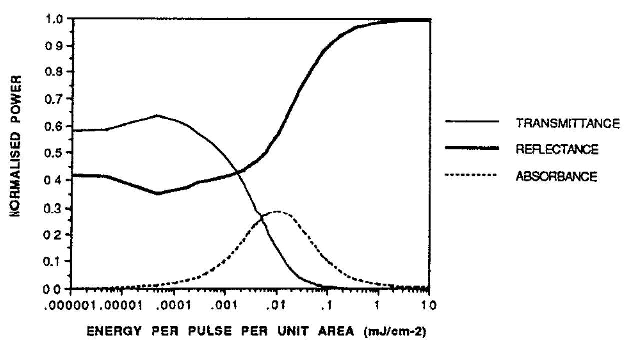



Fig. 2 Diagram illustrating the power requirements to switch a 94GHz linearly polarised beam using a 130µm silicon wafer at 45 degrees incidence, as a function of absorbed energy per unit area at 0.53µm.

The switching time is dependent on the duration and energy of the Q-switched pulse. What is important, for cavity dumping, is that sufficient energy be delivered in the first few nano-seconds of the pulse. It is also essential that the laser is free from any pre-pulse that may destroy the Q of the cavity before achieving significant power gain.

It is possible to shorten the duration of this pulse using non-linear techniques or by cavity dumping the Q-switched laser [7] but this adds extra complexity to the system. However, diode pumped micro Nd:YAG lasers may eventually offer the potential of a short pulse duration at reasonable energy levels (with good efficiency and relatively large modulation rates).

### Experiments

A Q-switched, frequency doubled, flash-lamp pumped Nd:YAG laser capable of delivering 6mJ of green light in 10ns was used in the switching experiments. The two laser beams were separated after doubling to prevent any pre-pulse effects due to infrared leakage. Laser pulses and millimetre wave pulses were measured using a HP 54111D fast sampling oscilloscope (2 Gsamples/s). The millimetre wave optics was designed using standard quasi-optical Gaussian beam techniques [9, 10] and used corrugated horns (manufactured by Thomas Keating Ltd), blazed HDPE lenses, and polarisers with 10µm tungsten wire at 25µm spacing and quasi-optical Faraday rotators [11]. A wideband mechanically tuned Gunn oscillator capable of operating between 75GHz and 100GHz was used as the source in all the experiments.

#### Delay line Experiment

To illustrate the ability of a quasi-optical silicon photoconductive switch to reflect power on short time scales, we have performed delay line experiments of the type illustrated in Figure 3. In this experiment the millimetre wave beam was focused down to a beam waist <5mm at the silicon switch. When the switch is open the silicon acts as a 40:60 dielectric beam-splitter and approximately one quarter of the power reaches the detector. When the switch closes, the millimetre wave power from the oscillator is dumped into the load. However, the power still in the delay line is now fully transmitted to the detector resulting in a short pulse. The length and size of the pulse is related to the switching and delay time.

Figure 4 illustrates typical results for a 6mJ pulse, where a 10ns delay resulted in almost full modulation of the signal. (Note that the apparent quick recovery of the switch is due to the bandwidth of the amplifier (10MHz-1200MHz) following the detector. The switch actually remains closed for several micro-seconds).

#### Cavity Dumping Experiment

The delay line experiment indicated that for significant power gains, using this particular switch, the round trip time should be greater than 5ns. This implies that one arm of a resonant cavity should be at least one metre long.

Because of the necessity of having a small beam waist at the silicon switch to reduce the laser energy required, this also requires that the resonator mirror, in the long arm of the cavity, be very large.

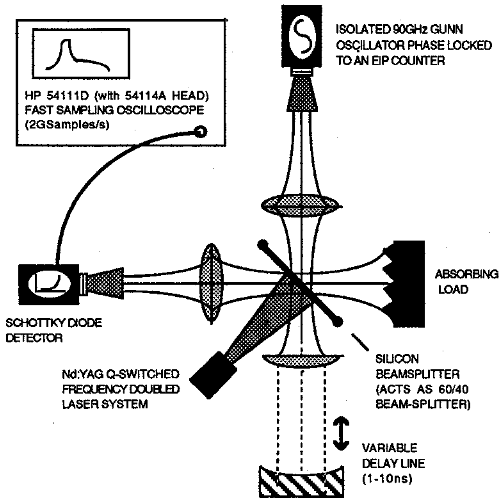
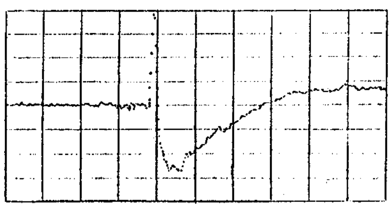
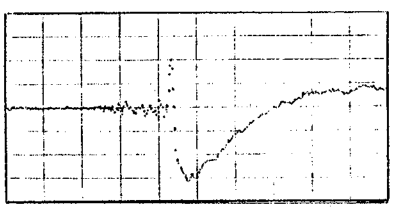


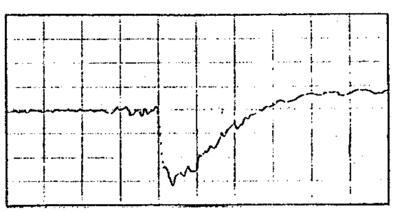

Fig. 3 Diagram illustrating schematically the variable delay line that was used to demonstrate speed of switching at different laser pulse energies. When the silicon switch closes an initial pulse is seen due to the energy stored in the delay line.



**DELAY OF 10.4ns (TIMEBASE 50ns/div.)**



**DELAY OF 6.8ns (TIMEBASE 50ns/div.)**



**DELAY OF 2.4 ns (TIMEBASE 50ns/div.)**

Fig. 4 Graphs showing the power transmitted to the detector in Figure 3 when the switch is closed for different delay times.

Figure 5 illustrates the optics that have been used in initial experiments to demonstrate the feasibility of cavity dumping. In this experiment the silicon sheet itself was used as a beam-splitter to couple power into the resonant cavity. The cavity was formed between a small (90mm diameter) mirror of radius of curvature 100mm and a large (1.0 metre diameter) mirror of radius of curvature 970mm. The mirrors were positioned to match in power for a beam-waist (<5mm) situated at the silicon beam-splitter. Another small mirror of radius of curvature 100.8mm was positioned to provide matched input conditions to the resonator.

Despite the 130μm beam-splitter having a reflection of around 40% it is still possible to completely match power into this three mirror system[1], and have a large circulating power. However, the alignment and positioning of all three mirrors becomes critical and finesses not much greater than 100 were achieved using this system. This implies a circulating power of only 30 times the incident power level.

When the silicon is switched the power is dumped from the long arm of the cavity, which has a round trip time of about 6 nano-seconds. A low loss quasi-optical circulator [9] enables measurement of the reflected power and provides isolation for the source, which otherwise would be load-pulled by the external cavity.[6] The source is phase locked by an EIP counter to ensure that the frequency of the Gunn oscillator remains on cavity resonance.

Figure 6 shows a typical result of a cavity dumped pulse at 94GHz of duration 8ns. The trace clearly demonstrates cavity dumping with a power gain of the order of 10. This compares to a calculated circulating power of around 30 times the incident power. In this experiment it was estimated that the laser provided at least 1mJ of green light within the first three nano-seconds and the illuminated area at the silicon was approximately 5cm$^2$.

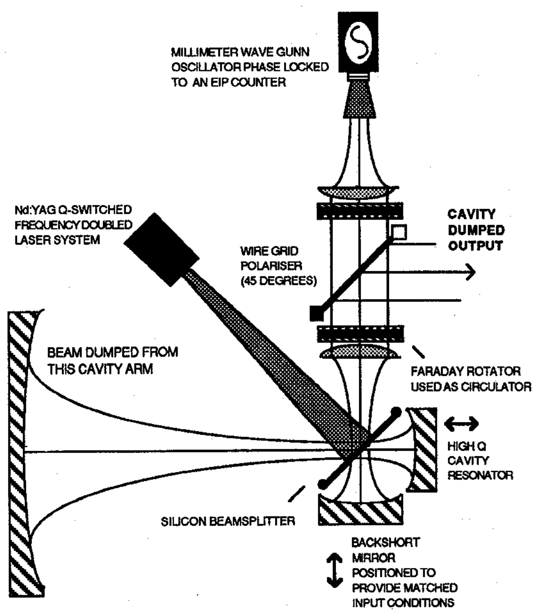



Fig. 5 Diagram illustating schematically the optics used to demonstrate quasi-optical cavity dumping.

## Discussion

The results obtained so far have clearly demonstrated the principle and feasibility of fast switching and cavity dumping. However, we believe that it is still possible to obtain large improvements in performance.

Firstly, it should be relatively easy to increase the circulating power and power gain by moving to thinner sheets of silicon (10-20μm). This will further reduce any small resistive loss and, more importantly, reduce the net reflection of the beam-splitter. This will reduce the tolerances on the positioning of the mirrors to obtain both impedance and spatial beam matching and increase the circulating power in the long arm of the cavity. When a low reflectivity polythene beam-splitter (<0.2%) was used in place of the silicon, it was found to be relatively easy to obtain finesses in excess of 600 for a matched cavity.

In addition, the amount of energy that was required to obtain effective switching was estimated to be an order of magnitude greater than that expected theoretically. Similar discrepancies have been reported by Yurek et al. [8] for silicon waveguides illuminated with a mode-locked frequency doubled Nd:YAG laser. We believe the most likely explanation are surface recombination effects. These may be very fast compared to the duration of the laser pulse, thus substantially reducing the effective carrier concentration.

Silicon has a relatively long bulk recombination time (many micro-seconds) and so was expected to remain in a quasi-metallic state long after an initial short laser pulse. However, the surface of the silicon wafers, used in the experiments, were very highly polished, which can create dislocations and recombination centres several microns deep. As the plasma is essentially formed in the top micron layer the effective recombination rate in this layer may be many orders of magnitude faster than in the bulk. Only those electrons that manage to diffuse into the bulk of the material create the long tail seen experimentally.

It is hoped that it will be possible to significantly reduce surface recombination effects by chemical etching and surface treatment of the silicon. This may substantially improve the switching time and reduce the laser energy required.

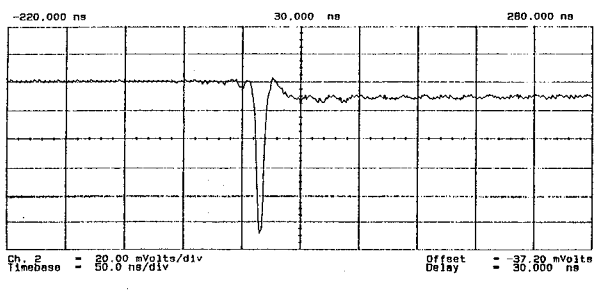



Fig. 6 Trace illustrating a typical cavity dumped output for a cavity finesse of 100, and the circulating power approximately 30 times the incident power. The power gain was estimated to be around 10. The timebase is 50ns/div.

## Conclusions

A thin silicon wafer illuminated by a fast Q-switched laser pulse has been used as a quasi-optical switch to cavity dump power from a microwave/millimeter wave open cavity. The switch has extremely low insertion loss and can switch on timescales of a few nano-seconds.

Further substantial performance improvements are expected at higher laser pulse energies (or shorter pulse duration's), and for much thinner silicon wafers. The reduction of surface recombination effects are also expected to substantially improve the performance of the switch.

The technique has great potential in allowing the creation of short high power pulses from conventional cw sources, and should work over very large frequency ranges.

## Acknowledgements

It is a pleasure to acknowledge useful discussions with Dr. A. Harvey, Dr. M.Padgett, Dr. P. Hirst, Dr. A. Maitland, and Professor J.W. Allen. We would also like to thank J.Terry and D.Withers for help with the laser system and M.Whyte and G.Radley for much of the mechanical construction.

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