# Experimental Multiple Frequency Injection-Wave Generator *

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## Abstract

The design of an optically activated multiple frequency injection-wave generator is presented. This generator naturally lends itself as a suitable microwave source for large phased arrays. The system consists of an output transmission line and static energy storage segments spatially placed with half wavelength separation. Each segment is isolated from the output line by a bulk GaAs switch. The injection-wave generator is initiated when the switches simultaneously are closed. The static electrical energy is then injected into the output transmission line, as defined by the spatial arrangement. The system is driven by a single 35 ps laser source whose output is divided by a fiber bundle for delivery to the individual switches. The versatility of the generator is demonstrated by the production of multiple frequencies. Experimental results are compared with simulation models.

## Introduction

Present RF and microwave sources used in military and civilian systems are inefficient in volume usage and in converting electrical energy to microwave energy. This situation requires an excessive use of electrical energy, volume, weight, and thermal management resources. The block diagram of a large radar system shown in Fig.1, indicating the components and their efficiencies, points to the large inefficiency of the transmit-receive or T/R module sub-system.

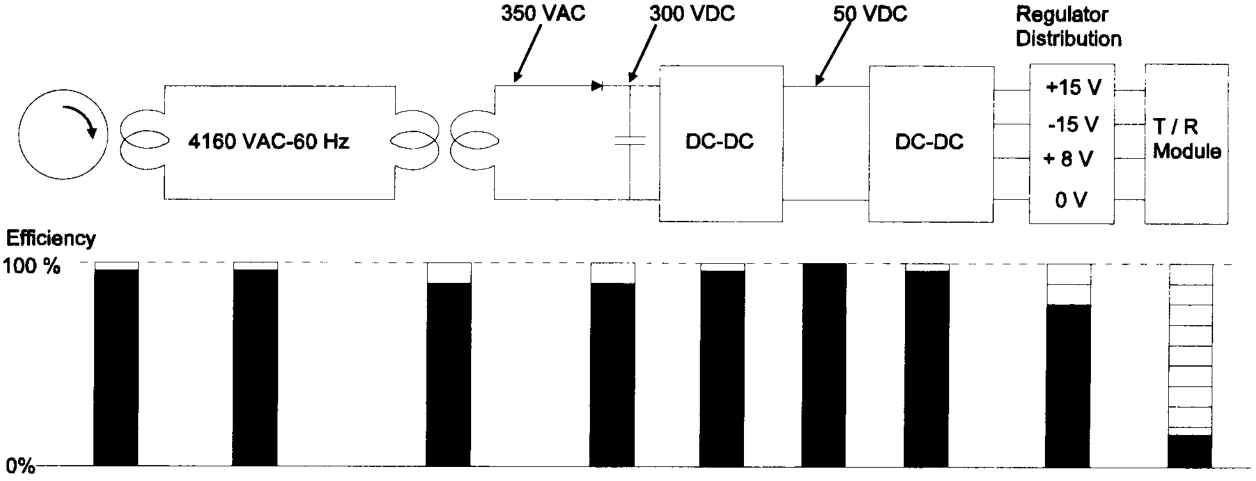

Figure 1. Illustration of modern radar power system and sub-system efficiencies

The efficiency in the T/R sub-system, presently about 12% overall, is due mainly to the inefficiency in amplifying the microwave signal to be radiated. Therefore, 8 times the desired output power must be generated since 7/8 of the supply power must be removed as heat. Thus, large reductions in system mass, volume, and thermal management systems can be brought about by increasing the efficiency of microwave power generation and/or amplification.

Present day microwave radar systems utilize class A amplifier circuits, with a maximum theoretical efficiency of 25%, to boost the microwave signal going to the antenna. Using the class B or AB amplifier configuration would increase the maximum efficiency to about 90% or an improvement of greater than three. Unfortunately, a class B or class AB

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amplifier arrangement is not easily configured because complementary (p and n type) high frequency active devices such as the MESFET (metal semiconductor) or HEMT (high electron mobility transistors) cannot be fabricated. Only n-type devices, using electrons as the majority carrier, have a sufficient gain-bandwidth product for high frequency application. The mobility of holes in p-type devices is much, much less than that of the electron and thus the gain-bandwidth product of a p-type device is much less than n-type devices.

## Photo-Switched Microwave Generation

Microwave energy can be generated directly from a dc power source using laser controlled, photoconductive semiconductor switches in a frozen wave generator (FWG) or an injection wave generator (IWG). The FWG system charges multiple half wavelength sections, connected by photo-switches, to opposite polarities. Closing all the switches simultaneously with a laser pulse releases the frozen wave to the load. Thaxter et al [1] produced a 6 GHz microstrip frozen wave generator with the performance limited by the carrier lifetime of the material and the energy loss through multiple series switches, rendering the circuit useful only for short-burst systems.

In contrast, the IWG system injects multiple half cycles into a common output line, each from a short transmission line, through multiple photo-switches. The injection wave generation system converts energy directly from DC into microwave energy using photoconductive switches. This approach has the potential to increase the overall electrical conversion efficiency of RF / microwave sources in the 1-50 GHz band by a factor of 4 to approximately 50% while reducing the volume of the source by a similar factors. Riaziat et al [2] discussed a lumped element based injection wave generator which first indicated that multiple pulses could be injected onto a common transmission line.

## IWG Design and Operation

The design of an IWG [3] begins with the selection of the highest frequency of operation desired, $f_o$, and the corresponding wavelength, $l_o$, in the substrate dielectric. Then multiple, quarter wavelength transmission line segments are connected to the output transmission line at half wavelength intervals along the output transmission line with photo-switches as illustrated in Fig. 2.

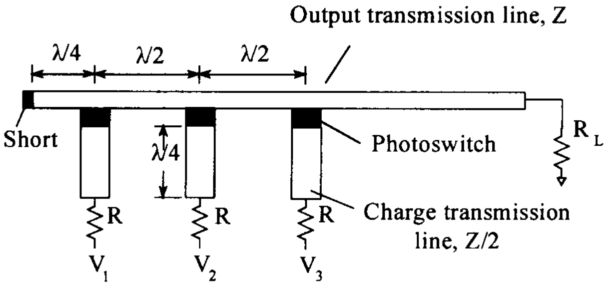

Figure 2. The basic IWG configuration.

The output power and the stripline material's dielectric strength define the plate separation of the transmission line. By matching the characteristic impedance of the output transmission line with the load impedance, the width of the transmission line may be found from the impedance equation

$$Z_0 = \frac{\sqrt{\frac{\mu}{\varepsilon}}}{(w/h)+2}, \tag{1}$$

where μ is the material's permeability, ε is the material's permittivity, w is the width of the stripline, and h is the conductor separation. The impedance of each charge transmission line is designed to be 1/2 of the output transmission line impedance since each charge section will see parallel segments of the output transmission line. This design thus matches source impedance to the load impedance for maximum power transfer and energy transfer efficiency.

With the closure of each photo-switch, electrical energy is injected into the output transmission line at spatial half wave locations simultaneously. Two waves are generated at each injection point, a forward wave moving toward the load, and a rearward moving wave moving toward a short at the end of the line. The rearward moving waves are negatively reflected by the short and follow the forward moving waves to the matched load after a time delay specified by the two-way transit time from the switch to the short. The forward waves from the switches sum together to form the first half of the RF burst. The rearward waves sum together and form the second half of the RF burst. Proper placement of the short provides the critical time delay for the two halves of the RF burst to sum correctly. Three alternately charged t-line sections yield the waveform illustrated in Fig. 3.

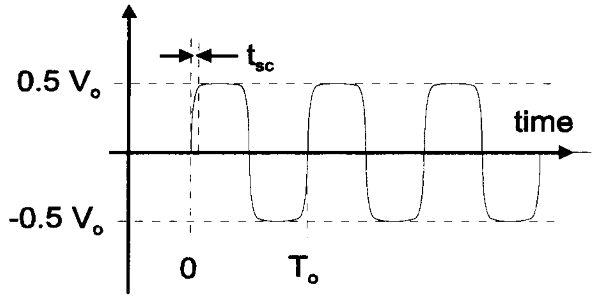

Figure 3. Illustration of IWG operation at highest frequency, $f_o$.

Thus each charged t-line section effectively generates one cycle. If a burst of 10 cycles is desired, ten sections are required. The source line segments can be charged in numerous ways to generate a wide variety of frequency and amplitude outputs. To generate the highest frequency possible, successive quarter wave sections are charged with alternating polarities. The generation process is initiated when all the photo-switches are closed simultaneously in a time, $t_{sc}$, that is much less than the period, $T_o = 1/f_o$ to generate the waveform.

The IWG is very frequency agile because the transmission line sections can be charged in a number of ways. For example, if pairs of the quarter wave sections are alternatively charged, the output waveform of Fig. 4 results in which the period of the output frequency has doubled. Note that this approach can be modified by changing the charging voltage on adjacent quarter wavelength sections. For example, if three adjacent quarter wave sections are charged to different voltages, a more sinusoidal waveform of Fig. 5 results.

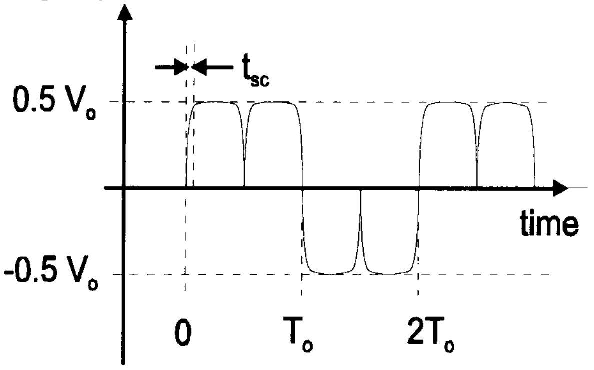

Figure 4. Illustration of alternate pair charging output waveform

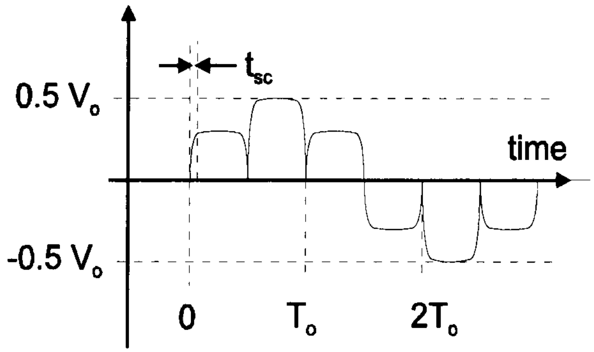

Figure 5. Illustration of charging amplitude on output waveform

In this sense, the IWG can be used to generate frequencies with periods that are multiples of the highest frequency period with the same optical input by changing the charging polarity and amplitude between burst.

The IWG system places specific requirements on the photo-switch. Linear photo-switches can be closed in a time approximately equal to the laser pulse width. Furthermore, linear photo-switches can be operated with pico-second jitter since closure is determined by the arrival of the optical pulse. The most difficult requirement is to minimize the interaction of each half wave length pulse with other quarterwave length sections.

Interaction is minimized when the switch closes in a time that is much less than the period of the highest frequency, conducts for one half period or $T_0/2$ and opens rapidly to prevent adverse loading of the output transmission line as the next half cycle passes by. The impedance of the ideal switch is illustrated in Fig. 6.

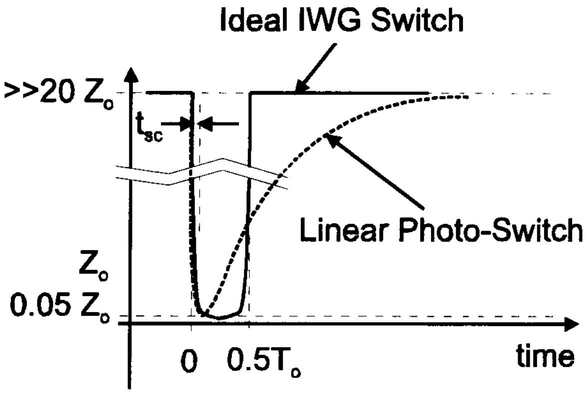

Figure 6. Illustration of switch impedance vs time

The impedance of a linear photo-conductive switch is illustrated in Fig 6, indicating that the linear photo-switch can be closed as required. However, the resistance of a linear photo-switch opens or recovers on a time scale determined by the recombination time of the material. For example, GaAs recombination time can be several ns; however, GaAs may be grown such that the recombination time can be tens of ps.

## Experimental Setup

An initial test setup was devised for a proof of principle experiment. A four switch IWG was fabricated, as shown in Fig. 7. The system was designed for a single charge element at each injection point to minimize timing problems due to jitter. The GaAs switches were fabricated for nonlinear operation at 5 kV by Sandia National Laboratory. However, the supply voltage was limited to ± 30 V.

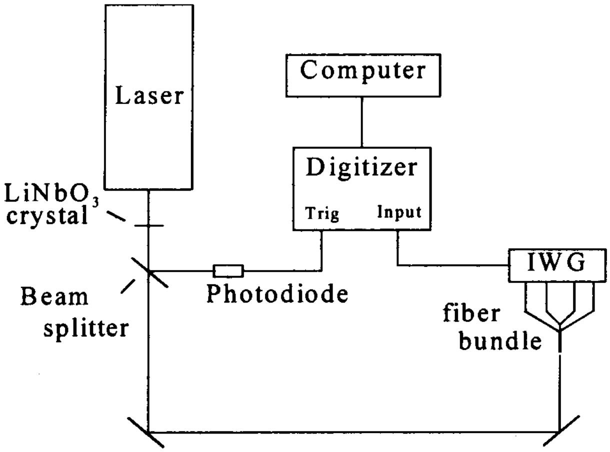

Figure 7. Illustration of Experimental Arrangement

The optical energy is delivered to each switch from a 35 ps Nd:YAG by equal length fiber optic cables, which are bundled on one end for the launching from the laser. The IR energy from the laser is frequency doubled using a lithium niobate crystal to produce the wavelength required by the bandgap of the GaAs switch. A Tektronics SCD5000 digitizer is used to capture the resulting RF waveforms at 200 Gbits/sec.

## IWG PSpice Model

A PSpice model of the four stage IWG was developed to guide fabrication and operation. A model for the linear photoconductive switch resistance using a finite closure time and the recombination time of the switch material was developed and included in the simulation. The initial operation at four cycles of the maximum frequency is simulated in Fig. 8 and the output at the next selectable frequency is illustrated in Fig. 9.

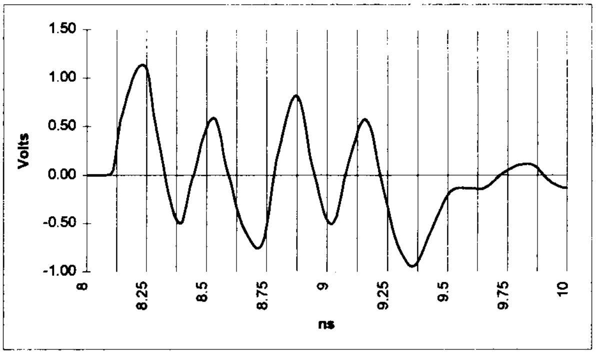

Figure 8. PSpice output of the IWG operating at the maximum frequency.

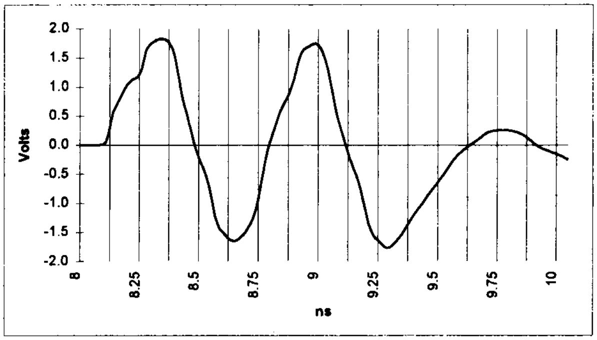

Figure 9. PSpice output of the IWG operating at 1/2 maximum frequency.

Each switch of the simulation operates identically with no time delay and is modeled from actual switch data. The results from the PSpice model reveal the distortion effects of the long recombination times of the switches, causing impedance mismatches which are readily apparent in these waveforms.

## Experimental Results

The initial waveforms produced by the IWG are promising and point to needed improvements in fabrication and the optical distribution system. The generator was operated at three allowable operating frequencies as shown in Figs. 9, 10, and 11. As predicted by the PSpice models, the generator produced the RF waveforms with varied success. However, as evident in the waveforms, problems with dispersion and impedance mismatches exists and must be addressed in future designs.

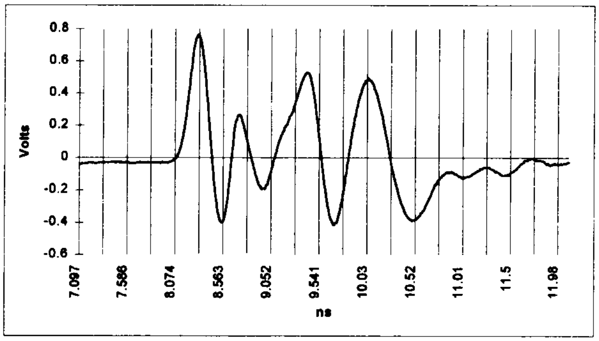

Figure 9. The IWG operating at maximum frequency.

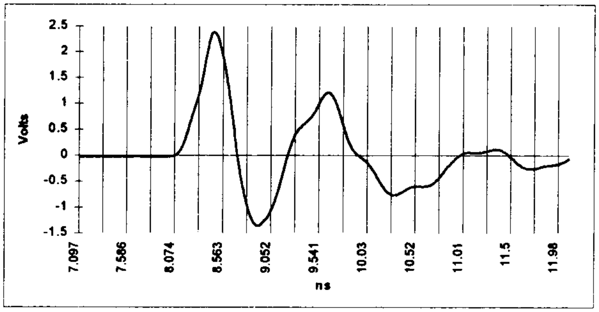

Figure 10. The IWG second selectable frequency.

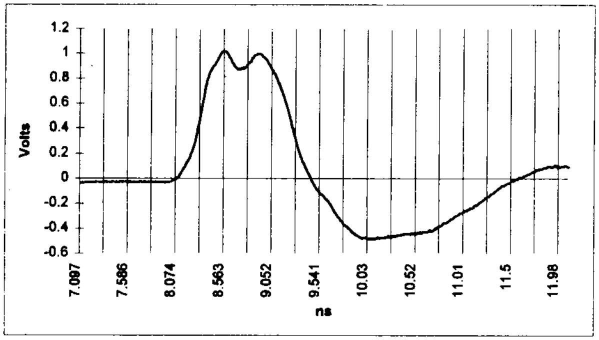

Figure 11. The IWG's lowest order frequency.

## Conclusion

The injection wave generator is presented as a viable alternative RF source to traditional methods currently employed. This experiment has shown that linear photo-switches can be used to generate multiple cycle, multiple frequency, microwave energy burst. Pulses can be added to form a series burst in a common output transmission line. The period of the output waveform can be lengthened by charging adjacent quarter wave sections in parallel.

The fidelity of the optical energy distribution system used in these experiments was insufficient and resulted in slower than necessary closure times which produced distortion of the output waveform. Single mode fiber bundles shaped to match switch dimensions, which minimize inductance by insuring uniform conduction across the switch, will be used in the future experiments.

The IWG efficiency, defined as the output pulse amplitude as function of charge voltage, can be close to 90% of the theoretical value, or half the charge voltage. Overall system efficiency, defined as microwave power out divided by the total power in, of 50% appears possible even with 50% optical energy transport efficiency and 30 percent laser efficiency (diode pumped solid state laser).

An on-off switch such as the Cu:GaAs switches developed by Schoenbach, et al is more appropriate for the IWG and will be investigated in future work.

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## References

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