Experimental 6-GHz Frozen Wave Generator with Fiber-Optic Feed

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***Abstract*— Experimental results from an optically activated 6 GHz frozen wave generator (FWG) test device are presented. The several system components needed to produce a low-cost monolithic pulsed power source suitable for large phased arrays are demonstrated. Static electric energy stored in 50 ohm microstrip transmission lines is released by fast GaAs photoconductive (PC) switches activated by 50 picosecond laser pulses distributed over fiber-optics. The present device is of hybrid construction, using commercial fiber-optic pigtailed integrated optic couplers and semi-insulating (SI) GaAs metal-semiconductor-metal (MSM) photoconductive switch chips bonded into microstrip. However, exclusive of the laser, the design lends itself to monolithic microwave and integrated optic techniques especially at high frequencies. Experimental test results compare well with circuit simulation predictions, showing that hybrid techniques introduce negligible parasitics at the design frequency. Lower resistance PC switches are needed to fully demonstrate the high power performance capabilities of this type of device.**

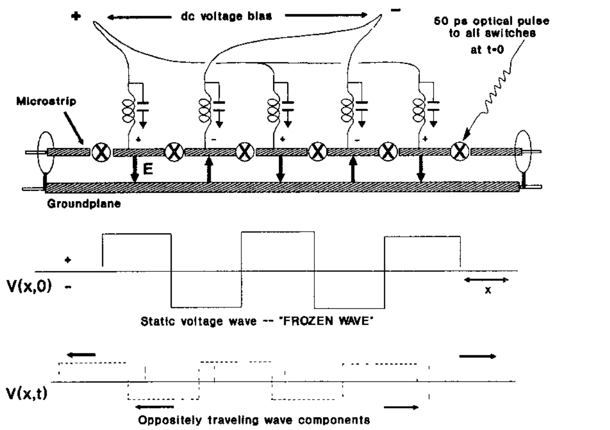

Fig. 1. Schematic of a five-line segment serially connected microstrip FWG test device with integral low pass bias filters having alternating bias polarity. See Fig. 2.

I. Introduction

FROZEN wave generators (FWG's) have been studied by a number of workers as a promising microwave source for short-pulse high-powered applications [1], e.g., wideband radar. Most of these applications use a few large coaxial lines, tens of centimeters long, charged to high voltage as energy storage elements with free space optical laser pulses activating rather large optical switches. While effectively demonstrating the exciting possibilities of the new techniques and laying a firm scientific ground work, the structures used are not easily extended to low cost fabrication or efficient distribution of light needed for practical phased array radar applications.

The present work applies these prior FWG techniques specifically toward use as efficient microwave sources in a multielement array. The FWG approach promises low-cost high-power arrays (we use this term for microwave phased array radiators) with the additional flexibility of pulse coding and shaping to tailor the spectral energy distribution on a pulse to pulse basis. Simple microwave circuits consisting of static energy storage microstrip transmission line segments and appropriately placed photoconductive (PC) switches may be located at the surface of the radiating aperture, thereby avoiding the dispersion and loss encountered by short or wideband pulses traveling through a long corporate feed. The static energy is released in a coherent microwave pulse by timing the closure of the PC switches using picosecond laser pulses in the proper sequence supplied to the array via an essentially dispersion free and lossless fiber-optic feed. The work reported here at 6 GHz uses hybrid techniques, but the basic design lends itself to further engineering to reduce it to nearly monolithic form where it may be made at low cost using thick film circuits and integrated optics. At higher frequencies, i.e., 50 GHz where the circuit size is sufficiently small, truly monolithic techniques may be possible by realizing a few inch diameter phased array emitting megawatts of peak power.

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II. Background

A FWG [2] or Hertzian [3] generator can have many forms. The configuration used in this work is shown in Fig. 1. A static bias potential (V_b) is established on serially connected equal length transmission line segments separated by small PC switches. A plot of line potential ($V_b(x,t)$) as a function of distance along the line (x) at $t = 0$ describes the initial "frozen" or static waveform. Here we use a simple alternating bias potential so each switch must withstand a voltage difference of $2V_b$. Simultaneously closing all switches at $t = 0$ results in the formation of a continuous transmission line allowing discharge of the bias in both directions along the line. Straight forward analysis of the transient behavior of the transmission line response shows [4]

$$V(x,t) = \tfrac{1}{2}V_b(x,0)(x - vt) + \tfrac{1}{2}V_b(x,0)(x + vt) \quad (1)$$

where $v = (LC)^{-1/2}$, v is the velocity of the $\pm$ traveling wave components and L and C are the inductance and capacitance per unit length respectively of the transmission line.

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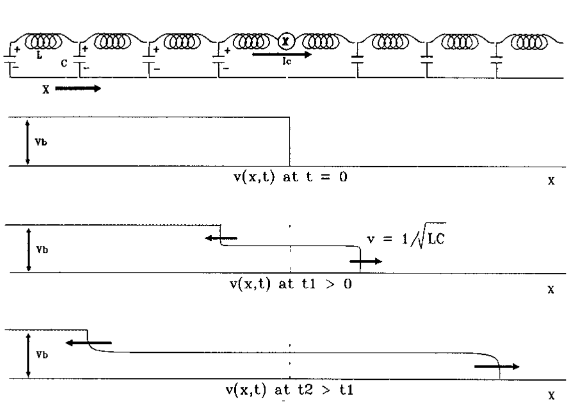

Fig. 2. Progressive discharge of the circuit model capacitors representing a uniform transmission line having an inital step in potential at t_0: $t_0 < t_1 < t_2$.

The dominant frequency of the pulse spectrum (f_c) follows directly from the frozen wave period, $\lambda = 2£$ where £ is the length of the line segment, and the velocity of the traveling waves

$$f_c = \frac{v}{\lambda} = (LC)^{-1/2}/2£; \quad \text{or} \quad £ = (LC)^{-1/2}/2f_c. \tag{2}$$

At 6 GHz, in 50 Ohm microstrip on an alumina substrate, the $\lambda/2$ line segments are about 1 cm long.

Physical insight into the creation of the two oppositely traveling half-height voltage waves of (1) can be gained by considering the lumped circuit analog of the distributed transmission line impedance for a simple step function waveform at time t_0 as shown in Fig. 2. Closure of the switch allows the nearest charged capacitor on the left to discharge into the nearest uncharged capacitor on the right. The discharge proceeds until the potential on the left drops to $V_b/2$ and the potential on the right rises to $V_b/2$. This cascading sequential discharge of the capacitance on the left and sequential charging on the right through the distributed inductance results in the two counter-propagating half-height wave steps shown at t_1 and later at t_2. Extending this concept to a double step or pulse using two switches closing simultaneously results in two half-height pulses traveling in each direction on the line.

III. Microwave Power Considerations of FWG

Additional important insight can be gained in conjunction with the circuit based relations of (1) and (2) by stepping back from the circuit concepts and considering the basic material properties involved, exclusive of a particular circuit. A dielectric medium having a maximum electric field breakdown strength (Em), volume (V) and dielectric constant (k) will have a static energy storage capability (Us) of

$$Us = \tfrac{1}{2}\int_V E \cdot D \, dV; \text{ leading to } Us/V = \epsilon_o k Em^2/2. \tag{3}$$

For nominal values of $E = Em = 10^6$ volts/meter and $k = 10$, as we see from (3), we get a value of 44 Joules/m^3 for the maximum stored energy density. If now we "somehow" arrange to extract this energy in the form of an electromagnetic wave, the maximum power density (Pa) or rate of energy extraction per unit area per second is determined by the velocity this energy travels through the bounding surface, where $v = c/\sqrt{k}$, leading to

$$Pa = (Us/V)v = \epsilon_o c\sqrt{k} Em^2/2 = 4.4 \times 10^9 \text{ Watt/meter}^2. \tag{4}$$

This significant power density, at the emitting aperture, is the maximum possible and in practice will be greatly reduced by the "somehow" above, which for the case of our FWG requires carving up and removing some of the dielectric energy storage volume to include circuit conductors, PC switches and space for optical access to the photoconductors. However, even if only 10% of the volume is used for energy storage we may achieve output power density approaching 44 kW/cm^2, or equivalently 1 MW output from 6 cm (or 2 inch) diameter aperture.

These insights emphasizing dielectric energy storage rather than transmission line circuits and lumped PC switches are presented to relate what we call the "new electromagnetics" [5], [6] to traditional FWG concepts. With the new technology static energy stored in slabs or wafers of polarized high permittivity photoconductors, such as Si, GaAs, InP, etc. is radiated directly into space using short high intensity optical laser pulses. Various experiments using spatial modulation of either the electric bias field applied to the photoconductor surface [6] or of the impinging light intensity [7] have demonstrated phase matching of the radiation with some directional control of the radiated beam. No microwave "circuits" need be used, the conductors only configure the bias field distribution. While traditional FWG technology is useful up to the hundred gigahertz region, the new techniques have been used to generate terahertz radiation. These considerations are included here to emphasize the connection between the technologies and point out the exciting engineering possibilities of combining the concepts to make electromagnetic sources in the spectral gap at high gigahertz frequencies using the immense optical power of modest sized ultrafast solid state lasers [8] capable of terawatt peak power levels.

Under ideal lossless conditions the peak power of the pulses (P) traveling out either end from such a capacitative FWG, shown in Fig. 1, is easily calculated. It is one half the energy (E) stored at $t = 0$ divided by the pulse duration (T), or alternatively, the squared amplitude of the voltage wave $(V_b)/2$ divided by the microstrip line impedance (Z_o)

$$P = E/2T; \quad \text{or} \quad = V_b^2/4Z_o. \tag{5}$$

Without going through analysis that is published elsewhere [9], as one might expect the limiting factor on microwave power, in the case of our serially connected FWG, to be voltage breakdown of the PC switch gap which sees a potential difference of $2V_b$ across a gap made as small as possible to strive for good switching efficiency. The gap length of our switches is nominally 100 micrometers and exhibit voltage breakdown over the surface of the GaAs at about 300 volts. If operated at a "probably" safe 200 V level, a 50 Ohm FWG of the type shown in Fig. 1 could produce up to 50 watts of peak power.

IV. Optical Power Requirements of FWG

The small gap is necessary to lower the switch ON-resistance (Ron) to be much less than Z_o. It is easy to show [9] that, in the limit of our case where the carrier recombination time is greater than the optical pulse width (see Fig. 4)

$$R_{\text{on}} = [hv/e\mu(\eta(1-r))Ep] * G^2 \qquad (6)$$

where h is Plank's constant, v-optical frequency, e-electronic charge, μ-effective charge mobility, η-quantum efficiency, r-optical reflectivity, Ep-optical pulse energy and G the gap length.

For a gap length of 10^{-4} meters and a value of 0.5 Ohms for R_{on}, and assuming a value of 0.1 for the $(\eta(1-r))$ term, we get a required pulse energy of approximately 0.1 microjoule for each PC switch, at an optical power density of 10 Mw/cm^2 for a 50 ps pulse. R_{on} must be much less than the microstrip line impedance to allow efficient discharge of adjacent line segments, minimizing the potential drop across the PC switch and maximizing the output voltage. Switch resistance comprises the photoconductor gap resistance plus the contact resistance of the metal/semiconductor interface.

The number of cycles possible, N, and upper frequency capability of a FWG are determined by the requirements on optical power, optical pulse width, and switch closure and opening time. We chose to build a six switch test device as a technical balance between a short wideband pulse (signal bandwidth proportional to $1/N$) and high pulse energy (proportional to N). The five-cycle pulse which distributes energy into 20% fractional bandwidth, is short enough to providing good radar range resolution. It also has enough cycles to allow fitting experimental results to the circuit model simulation to derive active switch characteristics. However, more cycles would require lower switch insertion loss and lower internal reflections to avoid waveform distortion.

To produce a faithful replica of the frozen wave our serially connected FWG requires all PC switches to close simultaneously in a time interval short compared to half a cycle of the FW and remain closed until all cycles of the pulse travel out of the device. Hence, for a five-cycle pulse at 6 GHz, closing time of much less than 80 ps and a closed interval of at least 800 ps are needed. The closing time for a linear PC switch follows the optical excitation closely and is not much longer than the full width at half maximum (FWHM) of the laser pulse. After the light pulse ends, the closed interval will be determined primarily by the carrier lifetime of the semiconductor which for SI GaAs is of the order of a nanosecond [10]. Experimental measurement of one of our SI GaAs switches, shown in Fig. 4, was done by switching out the voltage from a long uniformly charged 50 Ohm coaxial line. We see the rising edge in about 100 ps, which in this case is about the FWHM of the laser pulse, and the switch remains closed in the sense that it continues to switch out the charged lines voltage for about one nanosecond.

V. Fabrication of FWG

The microstrip energy storage lines with integral low-pass bias filter were designed using SUPER COMPACT [TM].

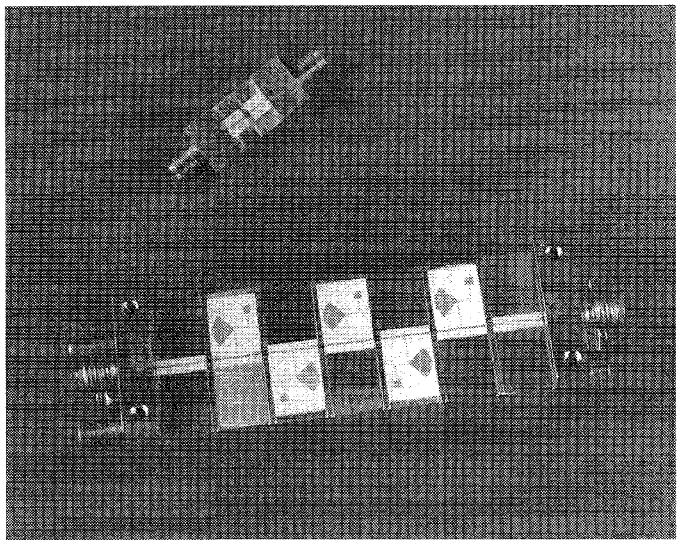

Fig. 3. Modular 6-GHz FWG test device. The microstrip line sections one centimeter long, seen as a line running down the center, are ribbon bonded to one millimeter square GaAs chips having a one hundred micrometer photoconductive gap. Narrow lateral lines with fan-shaped radial stubs comprise the low pass bias filter.

Fabrication was done commercially using thick film gold metalization on 0.25 mm alumina substrate with a gold ground plane. The design as seen in Fig. 3 is routine, having a quarter wave high impedance line and radial stub which is then connected to a square contact pad. Although, as seen from (5), for a given bias potential more power is generated with low impedance storage lines, we use 50 Ohm lines, both for ease of directly coupling to 50 Ohm measuring equipment and also satisfying the requirement that, for efficient switching, the on-state of the PC switch $R_{\text{on}} \ll Z_o$. S-parameter measurements of a single section of storage line with low-pass filter are shown in Fig. 5. The performance of the bias filter is seen to be adequate for the 20% fractional bandwidth needed for a five-cycle pulse. Storage line segments and GaAs PC switch chips are soldered to individual brass carriers which in turn are mounted on two steel drill rods with a central bolt as shown in Fig. 3. Coaxial to microstrip end carriers are added and finally the PC switches are ribbon bonded, to complete the microwave circuit. This modular approach turned out to be somewhat cumbersome, but was chosen for the test fixture to allow easy testing and replacement of parts because of expected difficulty making a single large six switch, five line segment device. Meaningful S-parameter measurements of the complete FWG are not possible because in the off-state S_{11} is near one, and the PC switches cannot be held in the on-state for more than about one nanosecond. Further tests of the device, described below, rely on fitting experimental measurement of the FWG output waveform to a simple P-SPICE [TM] model from which the switch ON-resistance and line losses can be determined and the internal impedance discontinuities can be inferred.

VI. Fiber-Optic Feed

Optical excitation of a PC switch requires a pulse energy of nominally one microjoule to drive the ON-resistance to be less than one Ohm, needed for good switching of a 50

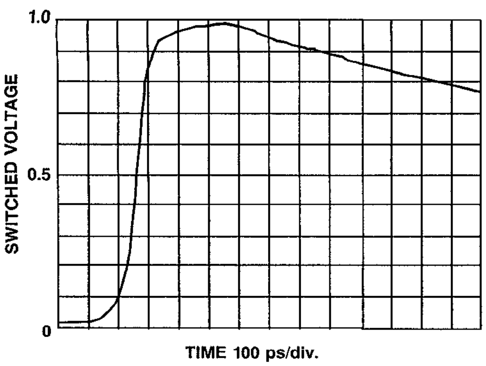

Fig. 4. Pulse response of GaAs switch to 30 ps optical pulses. The rise time (closure) is determined largely by the activating optical pulse width while the decay time (opening) is determined largely by intrinsic carrier lifetime of the GaAs semiconductor.

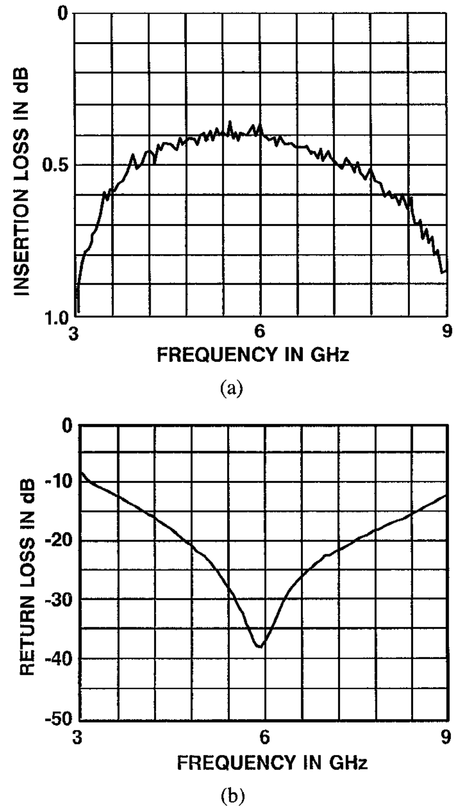

Fig. 5. Scattering parameters of microstrip line with low pass bias filter. The 0.4 dB insertion loss, shown in (a), was acceptable, but higher than expected from circuit simulations. Our five-cycle pulse requires the 20% fractional bandwidth shown in (b) for S_{11} MAG at -20 dB.

Ohm line. This follows from (6) which is valid for the regime of carrier recombination time much longer than the optical pulse width, which is approximately true for our SI-GaAs material [10]. We use a 10 Watt QUANTRONIX [TM] Nd:YLF (416) modelocked, Q-switched, pulse-picked, frequency-doubled laser to produce about 3 mW average power of 0.527 μm green 50 ps pulsed light at about 500 Hz repetition rate. This corresponds to about 5 microjoules total pulse energy at a peak power of about 100 kW. After six-way power splitting and allowing for at least a few dB optical insertion loss, the upper limit of power density available at each PC switch will be less than 100 Mw/cm^2, which is below the damage level of GaAs.

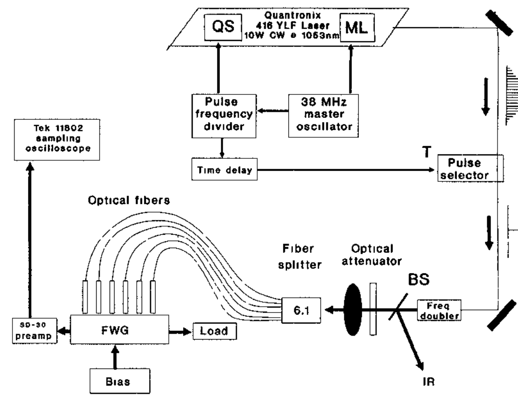

Fig. 6. Schematic overview of the optical setup. We measure only the signal wave traveling out one end of the FWG. The wave traveling in the other direction is absorbed in the matched load.

Distribution of the optical pulse energy and accurate positioning and sizing of the light spot on the six approximately 100 μm wide PC switch gaps can be done many ways. The method we demonstrate here, shown in Figs. 6 and 7, uses fiber-optics (FO) having a 1:6 fanout coupler and small spherical lenses to image the FO output onto the switch gap. The FO coupler is a Corning Photocor [TM] MGC 6010 with SDF [TM] pigtails of 100/140 μm (core/cladding) multimode fiber. For our optical pulse width and the short length of fiber used (about one meter) the total dispersion in the fiber does not cause measurable pulse broadening. Peak power density incident on the FO input pigtail is approximately 10^9 Watts/cm^2 which is near the damage threshold for silica. One must be careful coupling this large pulse into the FO. On one hand we want as much power as needed for efficient low resistance switching, but on the other hand neither accumulated nor catastrophic damage to either FO or integrated coupler can be tolerated. A straightforward technique to decrease possibility of damage is to scramble the single mode laser beam before it enters the FO input facet. This costs little in power budget since the optics can be arranged to place nearly all the light onto the rather large 100 μm diameter FO core of the coupler input pigtail. Once in the multimode FO, even if single mode upon entry, the light would be scrambled after going only a short way. We made a random phase or scatter plate by etching a microscope slide in hydrofluoric acid to mildly scatter the single mode beam. All the scattered light is then collected by a simple plano convex lens which images this scattering object onto the 100 μm FO core while keeping the light within the acceptance angle of the FO.

Proper operation of the FWG, as we are using it, requires all six PC switches to turn ON simultaneously to within a small fraction of the 166 ps period of the 6 GHz pulse or within about ± 5 ps. Therefore the optical path length through all six FO must be equal to within about ± 1 mm. The optical path length differences were measured using an optical carrier frequency from an Ortel, 0.85 μm wavelength, semiconductor laser modulated at 1.5 GHz by the Port-1 output signal of an HP 8510 automatic network analyzer. The FO coupler was the DUT whose output was demodulated by a photodiode coupled to Port-2. The FO input pigtail was spliced to the laser and

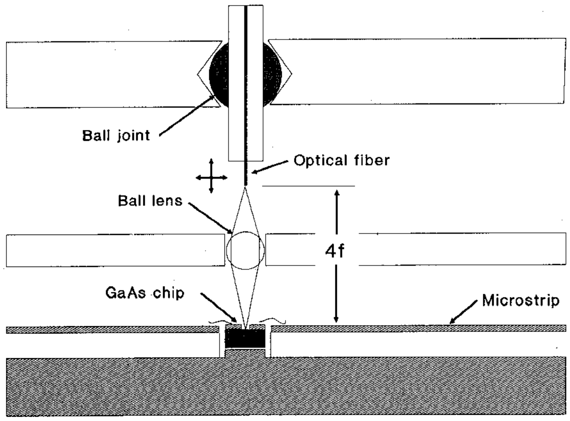

Fig. 7. Detail of optical coupling of fiber to PC switch. Three dimensional movement of fiber end allows imaging the fiber output facet onto the switch gap without fear of mechanically damaging the gap area.

the six individual output fibers were successively measured in phase length and cut. The RF period at 1.5 GHz is 666 ps resulting in measurement sensitivity of 1.85 ps per degree of phase. The largest spread in phase of 6.5 degrees, for all six FO, corresponds to 12 ps and was deemed adequate.

For FWG operation the six output fibers are coupled to the PC switches using 5 mm diameter ball lenses to image the FO end onto the switch gap, as shown in Fig. 7. The end of the FO, mounted in a standard ferrule, is positioned about $2f$ from the ball lens, which in turn is about $2f$ above the switch gap. The ferrule slides in nylon ball joint to allow three dimensional positioning of the FO image onto the switch gap at a magnification ratio near one.

VII. Experimental Results

The complete FWG test fixture with FO inputs, shown in Fig. 8, while definitely not monolithic and very hardware intensive, works well as a first test device. Much of the hardware shown is used coupling the light safely to the small PC switch. However, use of FO lines here to conduct the light is a convenience and the power splitting in the fan out coupler uses integrated optic waveguides which is a planar monolithic technique. We feel that combining integrated optics directly with monolithic microstrip can in principle produce a truly monolithic FWG that can be mass-produced at low cost. This approach also takes advantage of the immense power now becoming available from compact efficient solid state lasers capable of generating the picosecond trigger pulses required.

The measured RF output waveform, shown in Fig. 9(a), is observed directly through a wideband attenuator using a Tektronix [TM] 11802 sampling oscilloscope with a SD-24 preamp. The bandwidth of the system is limited to about 5 GHz by the oscilloscope delay line. The first two complete cycles are clearly seen with a period of about 180 ps. The expected waveform should be two and one-half cycles formed by the five sections of charged microstrip line. However, upon close examination of the device after the measurement, the bond wire connecting the fifth PC switch was found to be open. Comparison of the experimental results with a simple P-Spice [TM] simulation, shown in Fig. 9(b), using lossless transmission lines and resistive switches, with the fifth switch open, shows good agreement with the test data. Best fit is found for a switch resistance of R_{on} of about 30 Ohms. The small upward peak about 400 ps after the beginning in both the data and simulation is evidently the end of the forward going wave. The subsequent waveform is from the backward wave reflected at the open circuit bond at the fifth switch. The waveform fit is quite remarkable considering that for the simulation one assumes all switches are equal resistance.

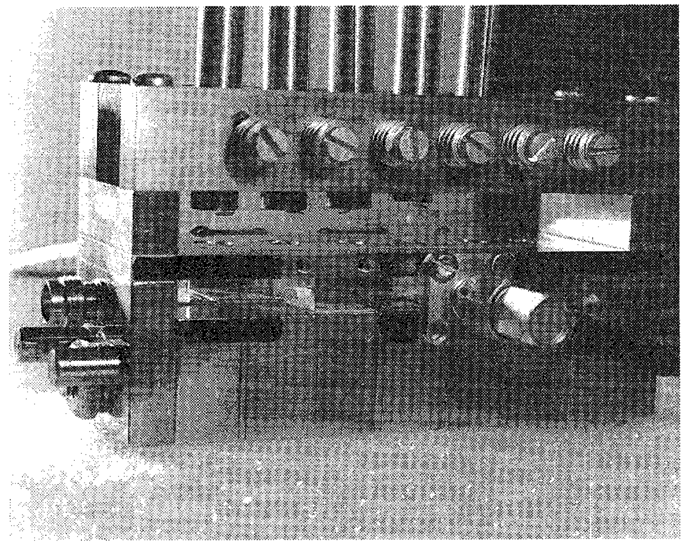

Fig. 8. Complete modular FWG test fixture. The vertical rods are ferules holding the optical fibers seen protruding from their lower ends. Below the fibers are seen the tops of the ball lenses which are mounted over each PC switch in the microwave fixture (which is shown by itself in Fig. 3).

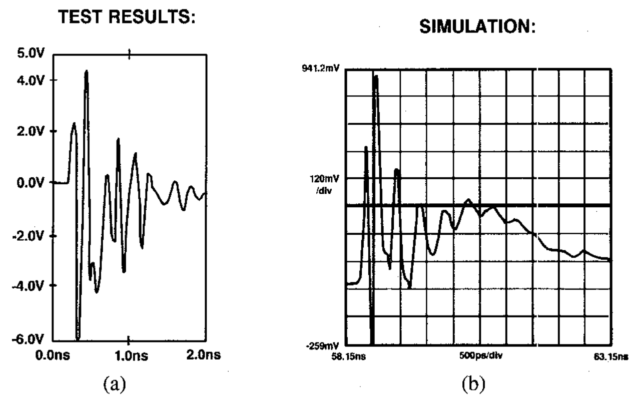

Fig. 9. (a) Performance of experimental FWG compared with (b) simple SPICE [TM] simulation. The switches in the simulation are considered as lumped, time dependant, resistors connecting ideal transmission lines without bias filter parasitics.

We were unable to improve the performance data of this test device over that shown in Fig. 9(a) even after the open bond wire was repaired. The primary problem was the inability to reduce the switch resistance below about 30 Ohms even with increased optical intensity. This limiting resistance is likely due to the contact resistance of the gold contacts and the semi-insulating GaAs. In attempting to improve the wave shape and output voltage by increasing light power several switches were damaged. Further iterations of this FWG using redesigned PC switches would be interesting, but is not being pursued at this time.

VIII. Special Considerations for Use in Phased Arrays

Use of FWG techniques in arrays offer several advantages including distribution of the electrical stress over many low power switching elements rather than depending on one high powered switch device. Also important is the ability of combining microwave power by beam forming in space rather than using complex and costly microwave circuit junctions. Both pulse shaping and array element phasing are done by routing and timing the optical trigger pulses incident on the many PC switches. This,in principle, gives a great degree of control of the microwave radiation, both spectrally and spatially, if the appropriate electrooptic (EO) control components are available for the fiber-optic feed. Although rapid advances are being made in this general area for optical communications networks, the relatively high-power EO components needed for an array feed are still in their infancy.

Underlying much of the renewed interest in FWG and related techniques is the rapid emergence of powerful picosecond all solid state lasers capable of generating sufficiently high peak power to afford distribution over the thousands of PC switches required in a modern phased array. For low cost phased arrays it is almost necessary to have simple circuits capable of being mass produced in as nearly monolithic form as possible.

IX. Conclusion

We conclude from this work that in the 6 GHz frequency range a hybrid thick film microstrip circuit with ribbon bonded GaAs PC switches performs as predicted from circuit simulation with negligible parasitics. Further, it is shown that activation by 50 picosecond optical pulses, even when fed through a multimode optical fiber power splitter, provides sufficiently fast rise time to faithfully produce the simulated microwave waveform. The modular test fixture design used allows imaging and positioning the fiber-optic outputs simultaneously onto the six PC switches, with micron accuracy, without fear of mechanically damaging the switches. Further work on the design of lower resistance PC switches is identified as the key to developing a truly practical FWG microwave pulsed power source.

Acknowledgment

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References

[1] E. S. Weibel, "High power rf pulse generator," *Rev. Sci. Instrum.*, vol. 35, pp. 173–175, Feb. 1964; J. M. Proud, Jr. and S. L. Norman, "High-frequency waveform generator using optoelectronic switching in silicon," *IEEE Trans. Microwave Theory Tech.*, vol. 26, pp. 137–140, 1978; C. S. Chang, M.-J. Rhee, Chi H. Lee, A. Rosen, and H. Davis, "Kilovolt sequential waveform generation by picosecond optoelectronic switching in silicon," in *Picosecond Electronics and Optoelectronics*, G. A. Mourou, D. M. Bloom, and Chi H. Lee, Eds. New York: Springer-Verlag, 1985, pp. 220–223.

[2] J. M. Proud, Jr., "Radio frequency generators," U.S. Patent 3 484 619, Dec. 16, 1969; H. M. Cronson, "Picosecond-pulse sequential waveform generators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 1048–1049, Dec 1975.

[3] D. H. Auston, K. P. Cheung, and P. R. Smith, "Picosecond photoconducting hertzian dipoles," *Appl. Phys. Lett.*, vol. 45, pp. 284–286, Aug. 1, 1984.

[4] C. R. Wylie, Jr., "D'Alemberts's solution of the wave equation" in *Advanced Engineering Mathematics*. New York: McGraw-Hill, 1960.

[5] Ch. Fattinger and D. Grischkowsky, "Point source terahertz optics," *Appl. Phys. Lett.*, vol. 53, pp. 1480–1482, 1988.

[6] B. B. Hu, n. Froberg, M. Mack, X.-C. Zhang, and D. H. Auston, "Electrically controlled frequency scanning by a photoconducting antenna array," *Appl. Phys. Lett.*, vol. 58, no. 13, pp. 1369–1371, Apr. 1991; J. T. Darrow, X.-C. Zhang, D. H. Auston, and J. D. Morse, "Saturation properties of large-aperture photoconducting antennas," *IEEE J. Quant. Electron.*, vol. 28, pp. 1607–1616, June 1992.

[7] B. B. Hu, J. T. Darrow, X.-C. Zhang, and D. H. Auston, "Optically steerable photoconducting antennas," *Appl. Phys. Lett.*, vol. 56, no. 10, pp. 886–888, Mar. 1990. X.-C. Zhang and D. H. Auston, "Generation of steerable submillimeter waves from semiconductor surfaces by spatial light modulators," *Appl. Phys. Lett.*, vol. 59, no. 7, pp. 768–770, Aug. 1991.

[8] G. Mourou and D. Umstadter, "Development and applications of compact high-intensity lasers," *Phys. Fluids B*, vol. 4, pp. 2315–2325, July 1992.

[9] W. C. Nunnally and R. B. Hammond, "Optoelectronic switch for pulsed power," *Picosecond Optoelectronic Devices*, C. H. Lee, Ed. Orlando: Academic, 1984, ch. 12; I. A. McIntyre, D. M. Giorgi, D. E. Hargis, and O. S. F. Zucker, "Optical requirements for light activated switches," *Optically Activated Switching*, SPIE vol. 1378, pp. 167–172; O. S. F. Zucker, D. M. Giorgi, A. Griffin, D. E. Hargis, J. Long, I. A. McIntyre, K. J. Page, P. J. Solone, and D. S. Wein, "Considerations of the limits and capabilities of light activated switches," *Optically Activated Switching*, SPIE vol. 1378, pp. 22–33.

[10] See, for example, H. Kressel, and J. K. Butler, *Semiconductor Lasers and Heterojunction LEDs*, New York: Academic, 1977, ch. 1.

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During his work at MIT Lincoln Laboratory in the Solid State Div. 8 from 1957–1967, he built and used millimeter wave spectrometers to investigate antiferromagnetic and acoustical properties of materials. He performed the first experimental measurements on thermal scattering of phonons in quartz at cryogenic temperatures at 70 GHz. From 1968–1983 he worked at Sperry Research Center where he studied electrooptic and photorefractive properties of various niobates for optical control and information storage applications. He demonstrated $(Sr,Ba)NbO_3$ to be an effective holographic storage material with novel electrically controlled latency properties. Also, at Sperry, he developed *in situ* optical diagnostic techniques capable of sub-angstrom resolution of sputtered thin film silicon on niobium layers used for superconducting Josephson junctions. In 1984 he joined the Rome Air Development Center, Electromagnetic Sciences Division (now Rome Laboratory, Electromagnetics and Reliability Directorate) at Hanscom AFB, MA. Working in the Component Technology Branch he has investigated surface and bulk acoustic waves properties useful for delay lines and signal processing devices at microwave frequencies. Most recently his work involves ultrafast optical switching of photoconductors for generating broadband microwave signals in the 10–100 GHz range.

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