GHz and 16.0 to 18.74 GHz. This performance demonstrates the feasibility of covering octave bandwidths continuously using monolithic technologies. Assembly problems, size, and repeatability of present hybrid VCO's should be vastly improved once this technology matures.

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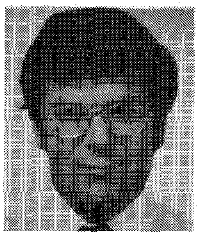
Mr. Scott has served as Program Chairman, Treasurer, Vice Chairman, and Chairman of the Dallas MTT Society, and was Chairman of the USF Student IEEE Section in Tampa, FL, in 1974. He has also served on the Dallas IEEE Section Awards Committee, and was the Administrative Vice Chairman in 1981. During the years 1979 to 1982 he served as Secretary to the 1982 MTT-S Symposium held in Dallas. He is also a Registered Professional Engineer in the State of Texas.



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An RF-Primed All-Halogen Gas Plasma Microwave High-Power Receiver Protector

HARRY GOLDIE, SENIOR MEMBER, IEEE, AND SUMAN PATEL

***Abstract*—A new type of keepalive for gaseous hybrid waveguide receiver protectors is shown to provide reliable and reproducible power limiting. The design allows halogen gases to be used in place of conventional gasfills, resulting in extremely fast recovery periods independent of duty cycle over a wide range. Recovery periods less than 100 ns were measured at incident power levels of 200-W peak at *X*-band frequencies using duty cycles up to 0.5.**

Manuscript received April 12, 1982; revised June 18, 1982.

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I. Discussion

Over the 40-year history of gas discharge TR cells, many techniques have been used to supply initiatory electrons necessary for microwave pulse breakdown. The dominant technique has been the dc-excited keepalive [1],

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[2], and, since 1970, the radioactive tritium ignitor [3]. In this paper we describe a new technique for supplying initiatory electrons that uses a miniaturized microwave power oscillator whose output energy is coupled through a narrow quartz capillary stem containing a low pressure gas.

The principles of operation are depicted in Fig. 1. The gasfilled quartz stem is located coaxial to a re-entrant resonant cavity with the re-entrant cone used for *E*-field enhancement. The RF coupled into the cavity creates in the stem a weakly ionized plasma whose free electrons diffuse from the priming discharge toward the waveguide signal gap. The critical distance between the two discharges (the CW priming discharge and the pulsed signal discharge) is determined by the gas type, the gas pressure, and the desired free electron density magnitude in the signal gap. This distance is determined by empirical techniques. The appropriate electron density in the signal gap can be determined empirically by measuring the excess wave-plasma interaction (insertion) loss due to the presence of the priming electrons, the pulsed threshold for gas breakdown in the signal waveguide, and the intensity of generated thermal noise available at the receiver port. These measurements, along with the necessary tradeoffs, were performed, and the results are presented below.

In this plasma limiter an important design concept involving halogen gases was realized which was not possible in previous TR cells or receiver protectors (RP's). It was possible to use halogen gases in all stages because metals are not in contact with the active plasma. Prior keepalive techniques used metallic surfaces within the gas cell, and therefore halogen gases, which rapidly form metallic halides under the influence of active plasma conditions, caused gas cleanup. By insulating the RF priming energy source from the chemical effects of the active plasma volume, we permit the use of chlorine gas.

Chlorine gas has a very high electron attachment rate, which leads to extremely rapid recovery periods at relatively high RF average power pulse levels. This recovery period does not change significantly with duty cycle or ambient temperature. However, the high electron loss rates yield a high threshold for ionization because, during the breakdown (avalanche period) and the steady sustaining period, the high electron losses require yet higher electron production rates to maintain a dynamic equilibrium in the plasma. Consequently, there occurs a higher RF breakdown power with an accompanying higher flat leakage power compared with that of RP's with conventional gasfills of $Ar+H_2O$. Fortunately the action of the p-i-n diode limiter is to complement the plasma limiter. The pulsed leakage from the chlorine plasma limiter contains high amplitudes but narrow widths followed by the flat leakage of considerably lower peak power for the remainder of the pulse. Thin-base p-i-n diodes are very suitable as limiters for high-peak-power narrow pulses, and they easily handle the (flat) pulse period at the lower peak amplitudes.

Another advantage of this concept is the elimination of the resonant TR window and the special metals (kovar) used to match the thermal expansions of glass-to-metal

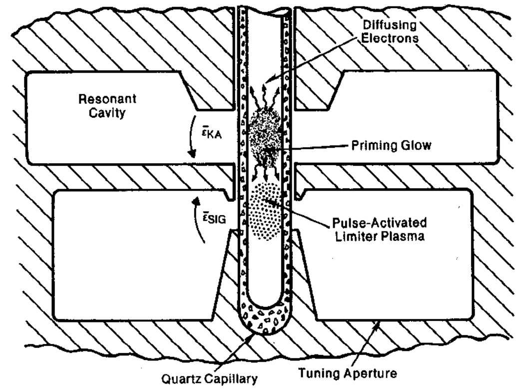

Fig. 1. Pictorial showing principles of RF power priming technique.

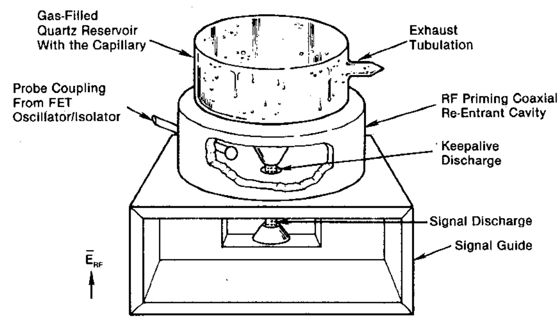

Fig. 2. Medium power waveguide plasma capillary-type limiter showing resonant cavity priming scheme.

junctions. The capillary limiter, when included as the medium-power ignitor limiter in a hybrid TRL,[1] can be manufactured as an all-aluminum cast RP. The elimination of the resonant windows significantly reduces insertion loss; we have measured an insertion loss of 0.1 dB for the stage at *X*-band.

Fig. 2 depicts the implementation of the concept as a waveguide limiter. The signal guide has an asymmetrical tuning aperture necessary to place the signal discharge adjacent to the priming plasma. The quartz stem is located coaxial with the cones in the tuning aperture. The spherical probe couples the priming energy from the power oscillator to the cavity through an isolator.

[1]TRL is commonly defined as transmit–receive limiter and refers to a solid-state p-i-n diode limiter cascaded behind a TR tube. However, the term TR tube is a misnomer since in modern radar systems the tube no longer switches or "sees" the transmitter power. In the earlier age of radar, when it was placed in a balanced duplexer configuration, or used singly as a shunt limiter in front of the receiver (90 degrees from the junction point connecting the radar antenna to the transmitter and receiver), the TR tube switched the transmitter burst. In the 1960's with the advent of high-power circulators and phase shifters, the RF transmitter pulse was directed to the antenna without the use of a nonlinear self-activated switch such as the TR tube. Therefore the "T" in TR tube does not function when the tube is used in a duplexing circulator network as a protector. A more descriptive term is RP (receiver protector), which is independent of the active media such as gas discharge, RF diodes or ferrites, or hybrid combinations thereof.

The foregoing definitions have been adopted by Subcommittee P457 on Standard Definitions of Terms for Nonlinear, Active, and Nonreciprocal Waveguide Components, sponsored by the IEEE/MTT-S Waveguide Standards Committee and approved by the IEEE Standards Review Committee on March 3, 1982. The definitions have been accepted for publication.

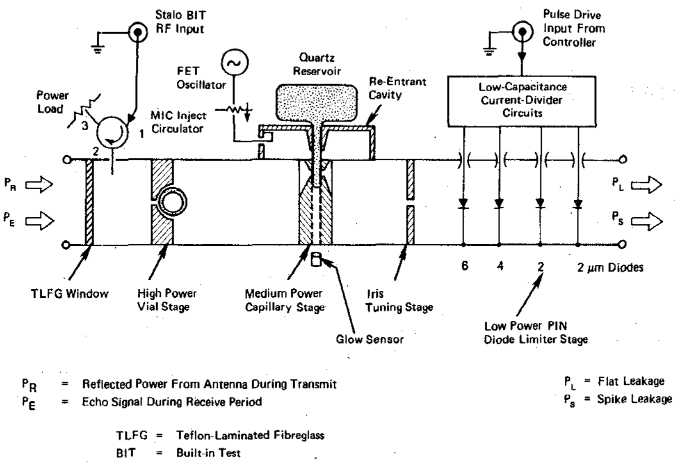

Fig. 3. Receiver protector schematic.

The inclusion of the capillary RF-primed limiter in an all-chlorine, solid-state hybrid RP is shown in Fig. 3. The variable-basewidth p-n junctions were selected to handle peak power levels from the capillary stage, to serve as passive limiters when the RF primer is quiescent, and during receive to act as a controlled attenuator for radar functions such as STC, noise AGC, and clutter AGC. The conventional chlorine vial stage placed at the input of the RP provides limiting operation up to 20 kW for short-term overloads and 5-kW peak for normal operation. The MIC isocirculator on the waveguide broadwall allows in-flight computer-controlled calibration of the 60-dB attenuator STC function.

Proof-of-principle experiments necessary to demonstrate the validity of the RF primer are discussed below. The important aspects that may be detrimental to its use, and which are studied in detail here, are the effects of the priming discharge as a generator of spurious responses, harmonics due to the priming oscillator that may reach the low noise amplifier, intermodulation products, wide-band thermal noise generated by the priming discharge, and, separately, the ability to achieve first-pulse breakdown over a wide variety of environmental conditions.

II. Experimental Model

An experimental model of the primed capillary limiter was assembled as shown in Fig. 4. The quartz capillary tubing had an OD of 1 mm, with a wall thickness of 0.18 mm, and was attached to a molecular reservoir. The quartz capillary assembly was chemically cleaned, evacuated, baked at 800°C, outgassed, cooled, gasfilled with 10 torr of reagent grade chlorine, and sealed. The resonant aperture (Fig. 4(a)) was tuned at X-band and measured to have a Q_L of 4 and an L_i of 0.1 dB at resonance. Note that losses of conventional single-stage dc (ignitor) cells have been measured at 0.3 to 0.4 dB.

The MIC FET oscillator (Fig. 4(c)) used 25 milliinch thick, 0.25-in thick ground plane, $\epsilon 10$ substrate in an aluminum carrier of $1.5 \times 1.5 \times 0.6$ in volume. This small volume allowed the RF source to fit between the waveguide flanges within the flange outline. The priming

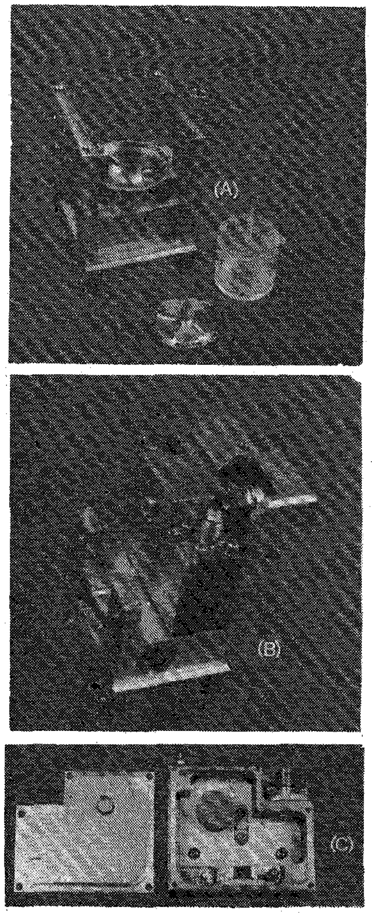

Fig. 4. Experimental model of capillary plasma limiter: (A) resonant cavity showing spherical coupling probe; (B) high power aluminum front stage with priming oscillator mounted; (C) microwave priming oscillator with lid removed.

frequency was selected to be 6.1 GHz and was based on the following criteria: 1) low-loss coupling through quartz at high energy density; 2) low ionization potential at 10 torr in Cl_2; 3) half wavelength kept the resonant cavity diameter suitable for X-band broadwall fit; 4) a fundamental frequency that would not propagate in the signal guide; 5) harmonics that would fall above the RF-amplifier band; and 6) finally but most importantly any existing IM products would fall outside the radar receiver bandwidth.

The RF priming source uses a GaAs FET in a reverse-channel oscillator circuit, which permits operation from a single power supply. The circuit is shown in Fig. 5. Oscillation takes place if the gate of the FET is presented with an impedance near zero Ω at that frequency. A quarter-wave open stub is effective, but the frequency can be better stabilized if a higher Q circuit is used. A dielectric disk resonator, having a dielectric constant of about 38, and of dimensions 10.5 mm diameter by 4.6 mm thick, is tightly coupled to the 50-Ω gate line, which is terminated in 50 Ω to eliminate spurious oscillations. The resonator is equivalent to a parallel-tuned circuit, and when spaced one-quarter wavelength from the gate the proper impedance appears at the FET gate. The spacing between the resonator and a disk attached to the top cover plate can be adjusted to fine-tune the oscillator frequency. The oscillator frequency

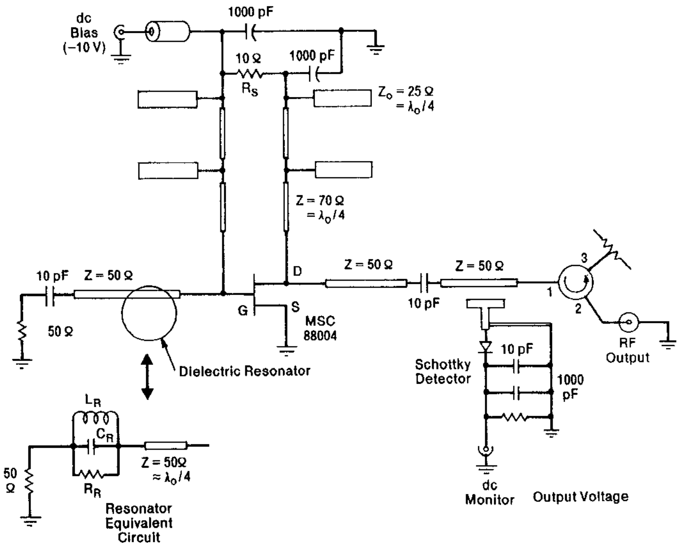

Fig. 5. Schematic of dielectric resonator stabilized FET power oscillator. Isolator mounted external to GaAs FET power oscillator. Isolator and detector monitor circuit is not shown in Fig. 4(C).

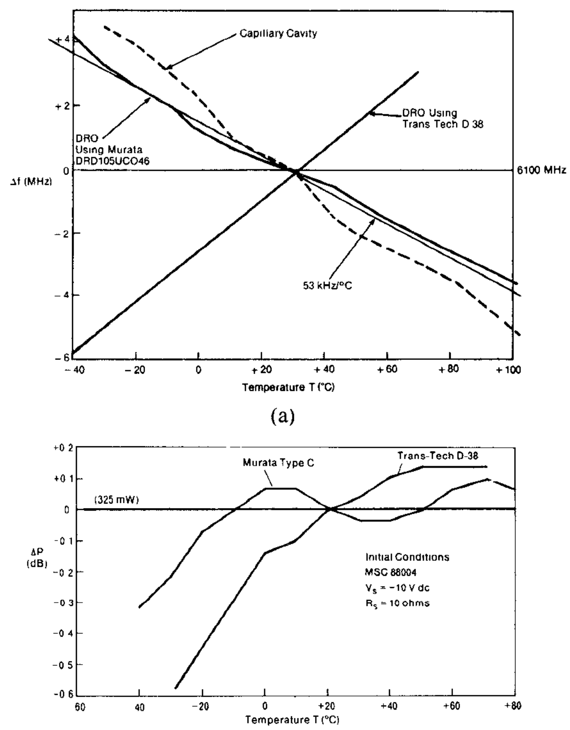

Fig. 6. Temperature characteristics of fixed-frequency FET oscillator and resonant cavity. (a) Dielectric resonator stabilized priming oscillator and capillary cavity resonance frequency versus temperature. (b) Output power variation with temperature.

changes less than 0.2 MHz for a 10-percent change in power supply voltage.

The frequency stability characteristic of the oscillator using two different resonator materials is plotted in Fig. 6(a), along with the resonant frequency of the capillary stage cavity. The slope of the oscillator frequency represents a change of approximately −15 ppm/°C. This is several times the temperature coefficient of the resonator alone, which implies that the temperature change of the transistor plays an important role in determining oscillator frequency.

The output power level is selected for minimum RP excess noise consistent with reliable priming by adjusting the bias resistor R_s. The nominal power level at the isolator output is 325 mW. The change in output power as a function of temperature is shown in Fig. 6(b). Output power is constant within ±0.25 dB from −40°C to +70°C, with the greatest change being a decrease at temperatures below 0°C. The present resonators were found to give much less change in output power than do conventional barium titanate ceramics. The output isolator is used to keep cavity resonance shifts from pulling the oscillator.

III. Experimental Results

A receiver protector (Fig. 3) was assembled and measurements taken to determine its characteristics. The resonant cavity was tuned to 6.1 GHz (it has a ±100-MHz mechanical tuning range) and its high level frequency response for ionization threshold was measured. The data (Fig. 7) shows that frequency drift of ±18 MHz from nominal will not cause the priming discharge to extinguish because the oscillator power does not fall below 270-mW CW. Independent measurements on the oscillator show (Fig. 6) that amplitude drift is under 0.25 dB; the frequency drift characteristics closely track that of the cavity so that no significant variation in excitation threshold occurs.

Ignitor interaction loss (Fig. 8) shows approximately 0.05 dB, which is comparable to conventional dc ignitors and indicates a free electron priming density of roughly 10^{10} e/cm^2, which is several orders of magnitude greater than that of the radioactive tritium ignitor. At a sustaining priming power level of 180-mW CW, the reflected and absorbed power was 90 mW; the minimum firing threshold is given in Fig. 7.

The thermal noise generated, a result of the electrons colliding with heavier particles in the active plasma, is shown in Fig. 9. The 325-mW data of 30°K is comparable to that of conventional dc ignitors.

A. Spurious Response

Placing an RF source and a microwave discharge in front of a low-noise amplifier in a modern fire control radar raises a valid concern regarding noise figure degradation and spurious in-band responses. Tests were conducted to determine if any interference problem existed. Using an HP 8566A spectrum analyzer, measurements at the RP-output port showed no measurable power at 6.1 and 18.3 GHz with a detection sensitivity of −96 dBmW. At 12.2 GHz a level of −86 dBmW was measured. With an RF amplifier having a 7-percent bandwidth connected, this out-of-band harmonic was significantly attenuated such that no measurable 12.2-GHz power occurred at the LNA output port (mixer input).

Measurement sensitivity was increased to −126 dBmW by using a 30-dB gain, 7-percent bandwidth, RF preampli-

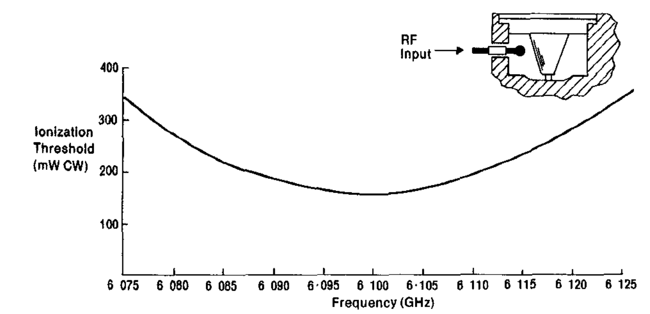

Fig. 7. Exciting threshold as a function of frequency.

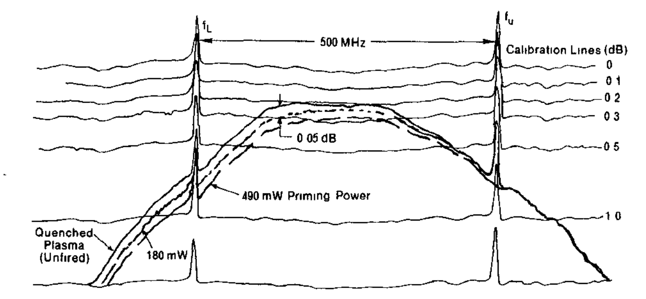

Fig. 8. Interaction loss.

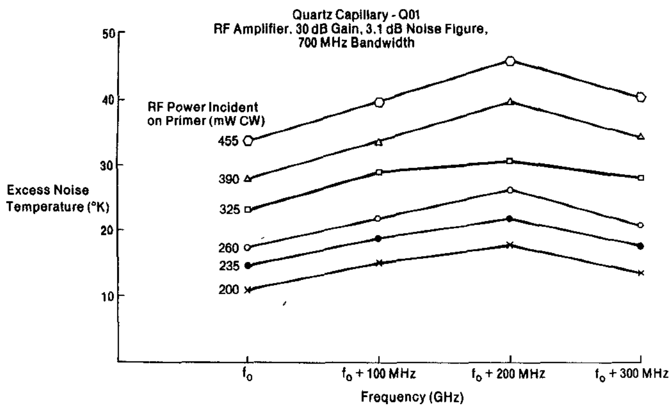

Fig. 9. Generated thermal noise of priming discharge.

fier of NF = 3.1 dB between the RP and the spectrum analyzer. A theoretical analysis of intermodulation distortion yielded critical frequencies for closer examination that would fall in the radar band. With the 6.1-GHz primer on, the LNA (low-noise amplifier) in cascade, and simulated echoes from -50 dBmW to $+20$ dBmW injected at the RP input port, no intermodulation products could be measured down to -126 dBmW.

IM tests were conducted on the RP/LNA in cascade and the third-order characteristic was plotted. It was found that the presence of the priming plasma had no measurable effect on the third-order product amplitudes, indicating that the primer did not act as a nonlinear mixing element.

B. First Pulse Breakdown

For a receiver protector to be an effective power limiter, it must create a discharge within a few nanoseconds on the first incident pulse and repeat the phenomenon reliably for pulse trains down to relatively low duty cycles. A test to measure this breakdown was conducted using a matched termination at 1 pulse/s with a 10-ns risetime, 0.2-μs pulse; the results showed an 8-W peak firing threshold with a 50-ns formative time lag. This is significantly greater (by a factor of 20) than that of a conventional dc ignitor but is satisfactory since p-i-n diodes as cascaded limiters can handle this leakage power and reduce the ignitor stage output power to levels under 50-mW peak. The gas discharge stage used need not have low output leakages, but rather they require output amplitudes that are power compatible with the solid-state p-n junctions. When the primer is turned off in the 1 pulse/s test above, the stage would not fire up to kilowatt power levels.

When the four-stage diode limiter/attenuator is removed from the unit under test and the primer is excited, the spike and flat leakage up to 10-kW peak (0.2 μs/450 Hz) do not exceed 500 W/8 ns and 5-W peak, respectively. It is interesting to note that the 0.5-duty 1-dB recovery period is under 90 ns for this test, but when the diode section is again inserted recovery increases to 125 ns, showing that the solid-state p-n junctions dominate the recovery characteristic. The RP insertion loss with and without the limiter is 0.8 dB and 0.2 dB, respectively.

C. Passive Limiting

The power that the RP can handle when the primer is off is determined by two factors: 1) the input p-i-n diode's I-region thickness and its thermal design, and 2) the firing threshold of the capillary stage under quiescent conditions. The capillary quartz assembly uses 10 μC of Pm^{147} to supply a small rate of initiatory electrons to allow the RF priming to start. Pm^{147} is a beta emitter and, even though the primer oscillator is off, depending on statistical fluctuations, a discharge occurs if the signal gap is strongly overvolted. Data shows that, at duty ratios above 4 percent, the RP acts as though a primer is not needed. At lower duty cycles and with the priming source off, input p-i-n diode burnout occurred at 700-W peak for 0.7-μs pulses; using a longer pulse of 2 μs, burnout occurred at 120-W peak.

D. Recovery Period, Leakage Power, and Low Level

Without rapid RP recovery times it is not possible for pulse doppler radars to function at the necessary high PRF rates. The results depicted in Fig. 10 show that for a 500 : 1 variation in duty cycle or average power the 1-dB recovery time varies less than 40 percent. The recovery period remains under 125 ns at power levels up to 200 W.

The spike and flat leakage for the gated and ungated p-i-n diode stage is shown in Fig. 11. The spikewidth is shown to be under 20 ns and is a result of the fast-acting p-n junctions rather than the RF-primed limiter. Spike leakage is under 50-mW peak, and flat leakage is less than 20-mW peak.

In high PRF radars it is necessary to prevent saturation of the receiver to prevent excessive LNA gain recovery

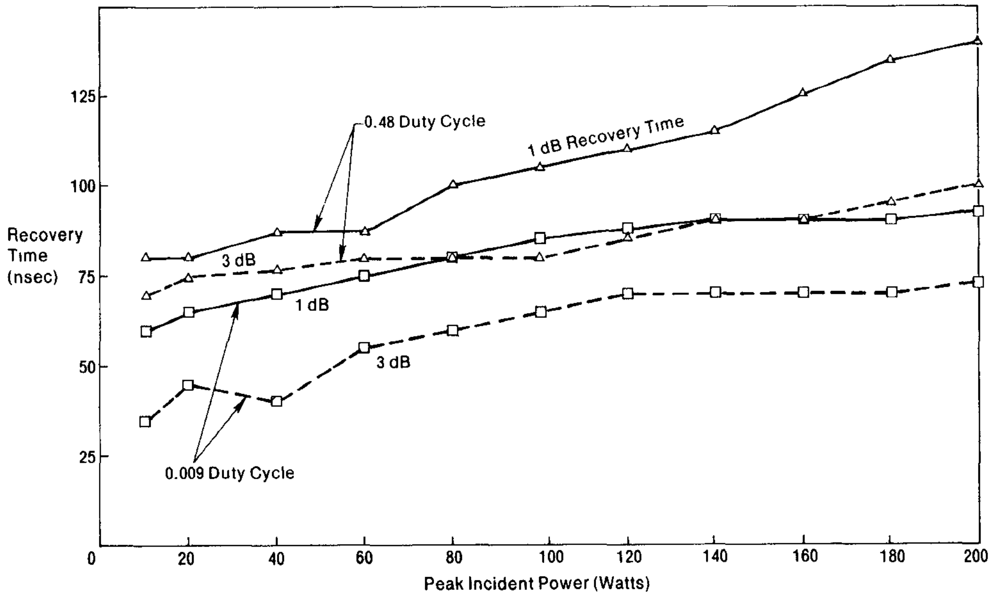

Fig. 10. Recovery time as a function of incident power over a 500:1 range of duty cycle.

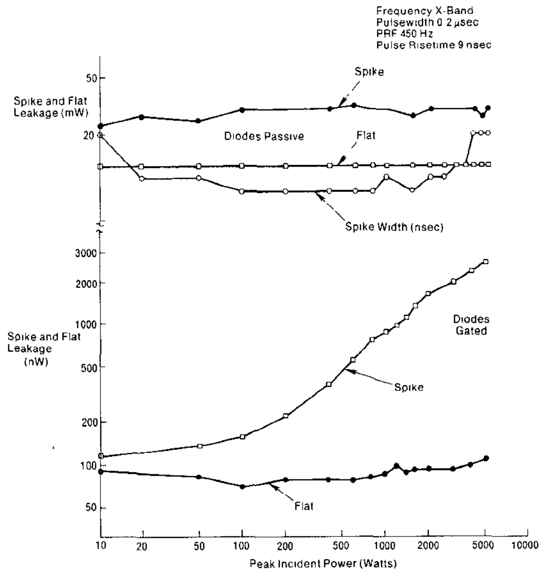

Fig. 11 Leakage characteristics as a function of incident power for gated and ungated diode modes.

time; therefore, the flat leakage requirement frequently must be under −30 dBmW. By gating the limiter synchronously with the transmitter, leakage power levels under −40 dBmW were achieved. The (gated) attenuation for the RP at 4-kW peak incident power was measured to be 106 dB within 20 ns of the arrival of the pulse.

At duty cycles above that shown in the figure, the leakage values decrease due to electron carryover. Residual free electrons carried over from a previous pulsed discharge increases the priming density for a subsequent discharge. The additional priming electrons lower the ionization potential; the worst-case leakage therefore always occurs at low duty.

Under active priming operation the RP can survive short-term 10× overload incident pulsetrains. Experiments showed that 15-s applications of 20-kW pulsetrains caused no measurable damage to the RP or to the FET LNA used as the receiver front end.

Modern RP's function not only as TRL's during the transmit period but also serve as precisely controlled attenuators on receive as STC, clutter AGC, and noise AGC's. Fig. 12 shows the RP low-level characteristics measured by a specially programmed automatic network analyzer. Insertion loss and VSWR over a 7-percent band was under 0.8 dB and 1.40, and the current-controlled attenuator yielded over 70 dB of attenuation. The eight curves, including the nonlinear diode limiting characteristics, are plotted automatically in 27 min.

E. Glow Sensor

The absence of the priming discharge, even for a single pulse, can result in p-i-n diode burnout. Therefore, it is necessary to use a small solid-state glow sensor (TI L-81) that can directly view the priming discharge and can be used to enable the transmitter. The sensor circuits are completely embedded within the RP envelope. The detected output current of the phototransistor, after temperature compensation, is fed to an LM741 op amp and then to an A/D where it is routed to the radar computer.

F. Life

Life testing of the oscillator and gasfilled quartz assembly in the resonant cavity has been underway since October 1980. Using 325-mW CW primary power from the oscillator, a total of 14 168 glow discharge operating hours has been demonstrated. Power has been cycled approximately one day off and 30 days on. The light output of the CW priming discharge is monitored by a phototransistor, and the load voltage, which is proportional to the light current,

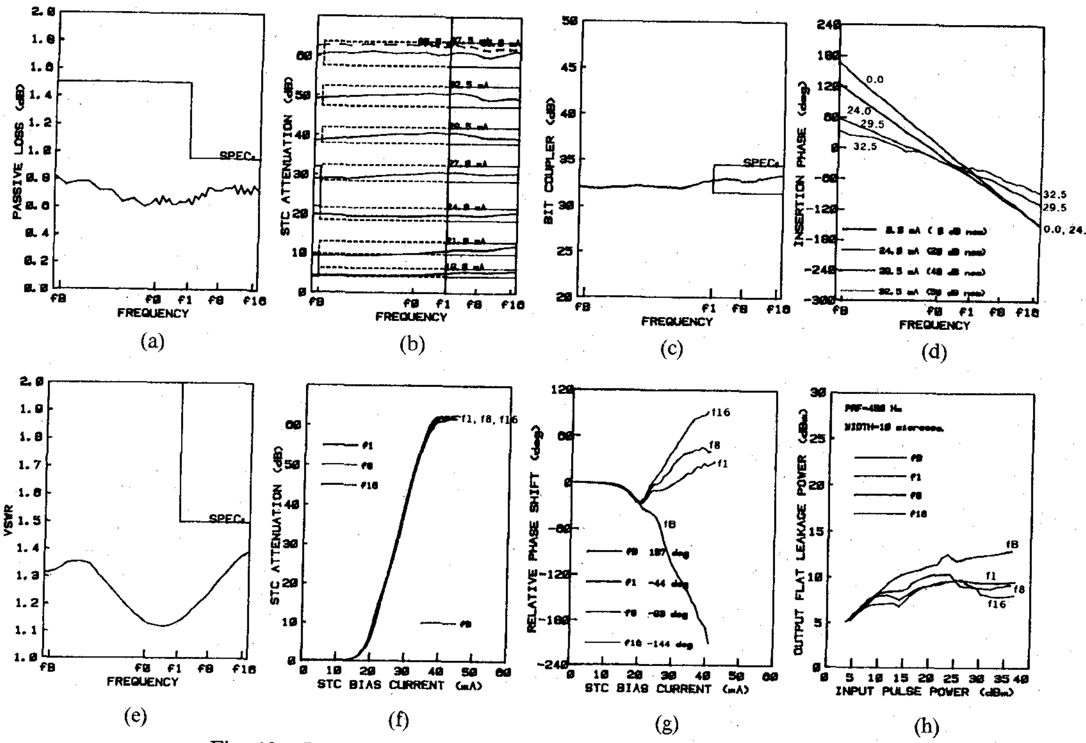

Fig. 12. Low-level characteristics measured on automatic network analyzer. Plot (h) shows nonlinear diode limiter data.

is recorded. No significant change in this parameter has been observed. Several units are undergoing flight evaluation with satisfactory results, and 10 units are now in pilot-line fabrication.

IV. Application

The microwave-primed receiver protector is used in high duty, high PRF radar systems that require extremely fast recovery time at high average power. Certain operational modes in PD fire control systems require recovery periods to be within 1 dB of the cold loss of the RP in 100 ns at average power levels of 100 W. Eight RP's that have achieved these parameters are now in the process of final assembly and are being readied for flight tests in an advanced radar system.

V. Conclusions

A new type of keepalive for receiver protectors (TRL's) has been demonstrated that uses microwave frequencies to provide a stable glow discharge for electron priming. Priming densities are comparable to the conventional dc 100-μA keepalive but without the attendant short life and metallic sputtering problems. Because metals are not in contact with the active plasma, halogen gases, with their rapid extinguishing periods at high RF power levels, can be used. Resonant windows and TR cell structures requiring kovar metals are eliminated and an all-cast-aluminum RP is possible. Intermodulation distortion tests and thermal noise tests show that no interference problems will occur with the RF-excited glow discharge. The RP is presently being evaluated in a fire control radar.

Acknowledgment

The FET oscillator was designed and developed by Dr. S. Stitzer of the Westinghouse Microwave Operations group.

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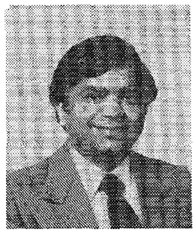
Mr. Goldie has served as chairman of the IEEE/MTTS Committee MTT-5 on High-Power Techniques since 1977, and is a member of

Subcommittee P457 on Standard Definitions of Terms for Nonlinear, Active, and Nonreciprocal Waveguide Components. He has published or presented over 35 papers on microwave control devices and holds 34 U.S. patents. He is also a registered Professional Engineer in the state of Maryland.



Suman Patel was born in Gujarat, India, on August 18, 1943. He received the B.S.E.E. with distinction in 1965 from Sardar Vallabh University in Anand, India. During his graduate program at the University of Delaware, Newark, DE, he worked as a Teaching Assistant and Research Fellow. The University awarded him the M.S.E.E. in 1968 and the Ph.D. in electrical engineering in 1973.

He worked for Norlin Communications in Gaithersburg, MD, for five years in the RF surveillance receiver and signal distribution groups, where he was engaged in RF component design, systems analysis, and automatic test software development. Since February 1979 he has been with the Microwave Operations Group of the Westinghouse Defense and Electronic Systems Center in Baltimore, MD, where he is responsible for developing high-power gas discharge and solid-state receiver protector devices for ground, shipboard, and airborne radar systems.

Wide-Band Subharmonically Pumped *W*-Band Mixer in Single-Ridge Fin-Line

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Abstract —**A subharmonic mixer is described that has an instantaneous bandwidth of 11 to 14 GHz centered near 95 GHz. A wide bandwidth is achieved by the close integration of a low-capacitance diode mount, printed circuit matching elements, and simple yet effective filters which are uniquely suited to realization in a single-ridge fin-line. The mixer also has a two-terminal shunt mount that will accept two conventional beam-lead diodes or a single dual-junction device. With the latter, a minimum conversion loss of 8.5 dB has been achieved with a drive level of only 4 dBm at 45 GHz.**

I. Introduction

SUBHARMONICALLY pumped mixers have been constructed in various transmission media including stripline [1], microstrip, waveguide [2], and double-ridged fin-line [3]. Although excellent results have been obtained at millimeter wavelengths [4], tunable waveguide back-shorts have so far limited the instantaneous bandwidth. The existing shunt mounts accommodate two diodes rather than the latest dual-junction antiparallel devices [5], [6]. Since these mounts are susceptible to asymmetric bonding resulting in degradation [7], a two-terminal mount would be ultimately preferable. A wide-band fin-line mixer with a two-terminal shunt mount and unique RF/LO filters is described.

II. Circuit Description

Fig. 1 shows the construction features of the wide-band single-ridge fin-line mixer. The fin-line is printed on 5-mil Duroid which is suspended in the E-plane of a rectangular housing. The housing, in the indicated region, has the same inner dimensions as WR-10 waveguide. The gap (d) between the edge of the fin and the upper housing wall is chosen to be small enough to propagate the subharmonic local oscillator (LO), yet large enough to accommodate the antiparallel diodes. By selecting a gap ratio (d/b) equal to 0.3, the cutoff frequency of the fin-line is placed at 37 GHz which is well below the intended LO band.

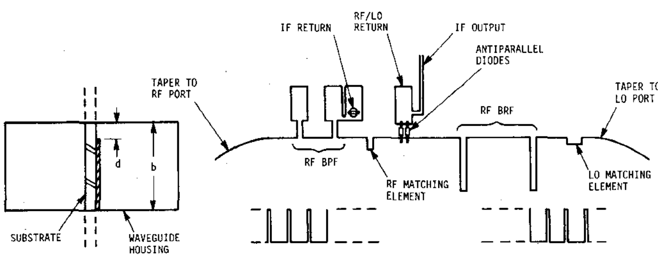

Fig. 1. Subharmonic mixer in single-ridge fin-line.

The RF signal enters from the left and passes through a cosine taper, matching the fin-line to a standard WR-10 port. The signal then passes through a single-section band-pass filter (BPF). The filter is formed by two inductive strips each joining the edge of the fin to a ground return. Grounding in the RF and LO bands is achieved with low-impedance stubs within the choke region [8] of the housing. Grounding in the IF band is provided by a feedthrough that links the illustrated pattern to a rear-surface metalization. After exiting from the BPF the signal passes through the RF matching element and reaches the antiparallel diodes which are reactively terminated by the

Manuscript received March 15, 1982; revised July 15, 1982. This work was supported in part by NOSC under Contract no. N00123-79-C-1879.
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0018-9480/82/1200-2184$00.75 ©1982 IEEE