AN RF-PRIMED ALL-HALOGEN GAS PLASMA MICROWAVE HIGH POWER RECEIVER PROTECTOR

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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 nsec were measured at incident power levels of 200 watts peak at X-band frequencies over a duty cycle range of 0.00005 to 0.5.

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 [1,2] 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.

Operation

The principles of operation are depicted in figure 1. The gasfilled quartz stem is located coaxial with 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 priming electrons, the pulsed threshold for gas breakdown in the signal waveguide, and the intensity of generated thermal noise available to the receiver port. These measurements, along with the necessary tradeoffs, were performed, and the results are presented below.

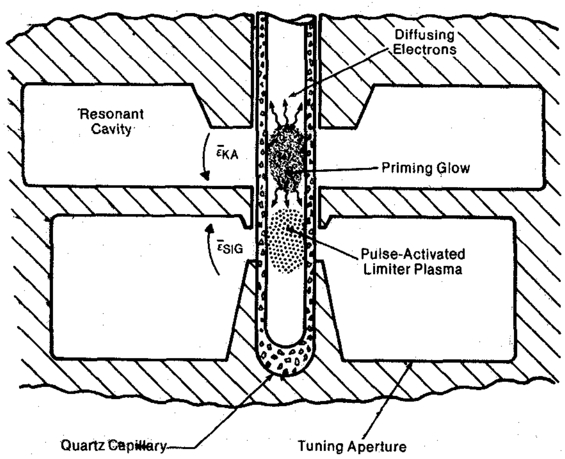

Figure 1. Pictorial Showing Principles of RF Priming Technique

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). Halogen gases were used in all stages because no metals are in contact with the active plasma. Prior keepalive techniques required metal 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 PIN 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 PIN 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 junctions. The capillary limiter, when included as the medium-power ignitor limiter in a hybrid TRL, can be manufactured as an all-aluminum casting. 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.

Figure 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.

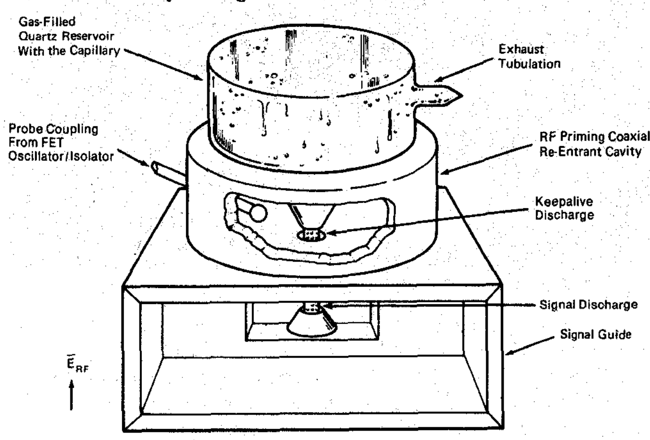

Figure 2. Medium Power Waveguide Plasma Capillary-Type Limiter Showing Resonant Cavity Priming Scheme

The inclusion of the capillary RF-primed limiter in an all-chlorine, solid-state hybrid RP is shown in figure 3. The variable basewidth PN 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

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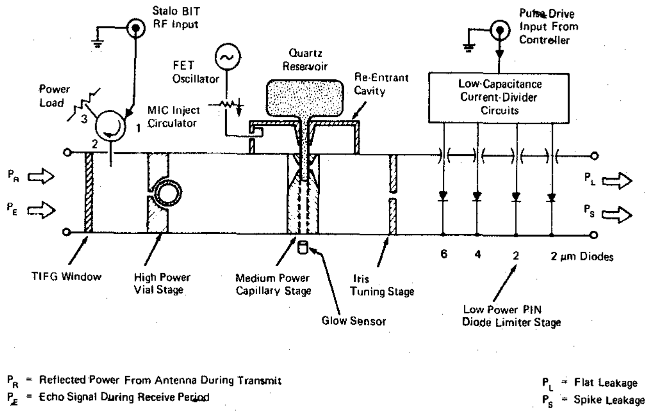

Figure 3. Receiver Protector Schematic

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 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, wideband thermal noise generated by the priming discharge, and, separately, the ability to achieve first-pulse breakdown over a wide variety of environmental conditions.

Experimental Model

An experimental model of the primed capillary limiter was assembled as shown in figure 4. The resonant aperture (figure 4B) 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.

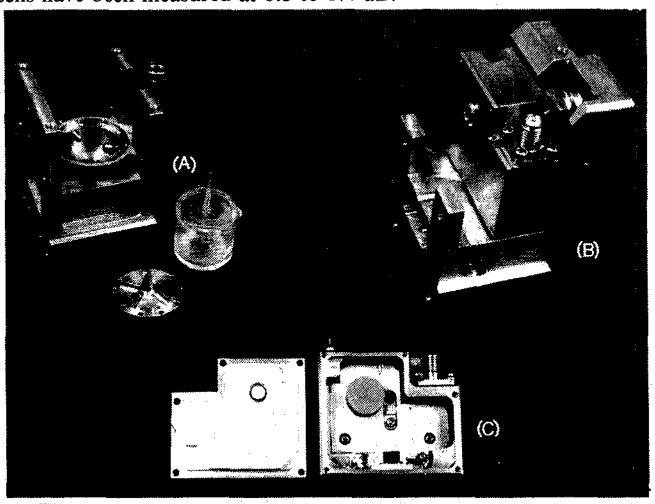

Figure 4. Experimental Model of Capillary Plasma Limiter

The MIC FET oscillator (figure 4C) used ϵ 10 substrate in an aluminum carrier of 1.5 x 1.5 x 0.6 inch volume. This small volume allowed the RF source to fit between the waveguide flanges within the flange outline. The priming 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 that permits operation from a single power supply. The oscillator frequency has been stabilized by a disk resonator with a dielectric constant of about 38. The oscillator frequency changes less than 0.2 MHz for a 10 percent variation in power supply voltage. The output power level is selected for minimum RP excess noise temperature consistent with reliable priming, and the bias voltage is adjusted to deliver 350 mW nominal power at the isolator output at 6.1 GHz. The oscillator power is constant within ±0.25 dB and the frequency shift is within ±3 MHz over a temperature range of −40°C to +70°C.

Experimental Results

A receiver protector (figure 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 (figure 5) 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 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.

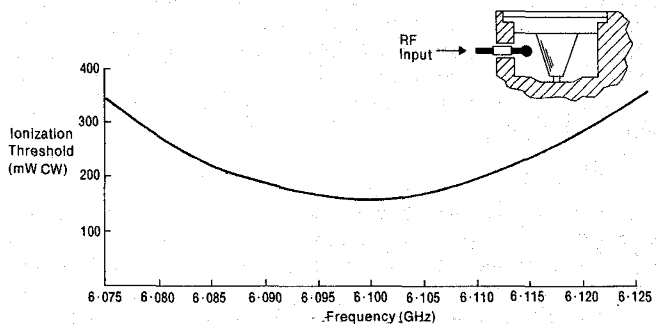

Figure 5. Exciting Threshold as a Function of Frequency

Ignitor interaction loss was measured to be 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 figure 5.

The thermal noise generated, a result of the electrons colliding with heavier particles in the active plasma, is shown in figure 6. The 325 mW data of 30°K is comparable to that of conventional dc ignitors.

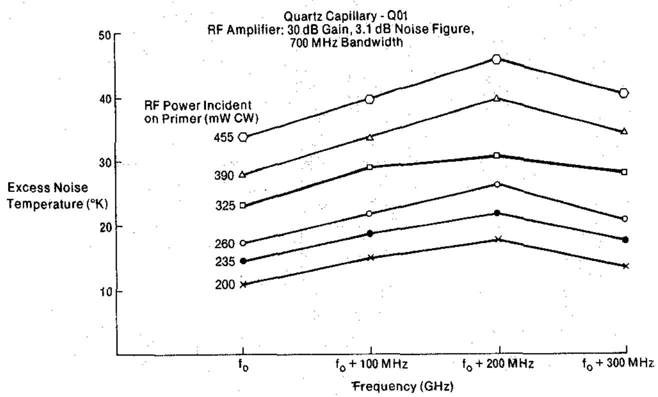

Figure 6. Generated Thermal Noise of Priming Discharge

a. Spurious Response. 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 the RF amplifier 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, 5 percent bandwidth, RF preamplifier of NF = 3.2 dB between the RP and the 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 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.

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/sec with a 10 nsec risetime, 0.2 μsec pulse; the results showed an 8 watt peak firing threshold with a 50 nsec formative time lag. This is significantly greater (by a factor of 20) than that of a conventional dc ignitor but is satisfactory since PIN 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 PN junctions. When the primer is turned off in the 1 pulse/sec test above, the stage would not fire up to kilowatt power levels.

c. Passive Limiting. The power that the RP can handle when the primer is off is determined by two factors: (1) the input PIN 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. Input PIN diode burnout occurred at 700 watts peak for 0.7 μsec pulses; using a longer pulse of 2 μsec, burnout occurred at 120 watts 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 figure 7 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 nsec at power levels up to 200 watts.

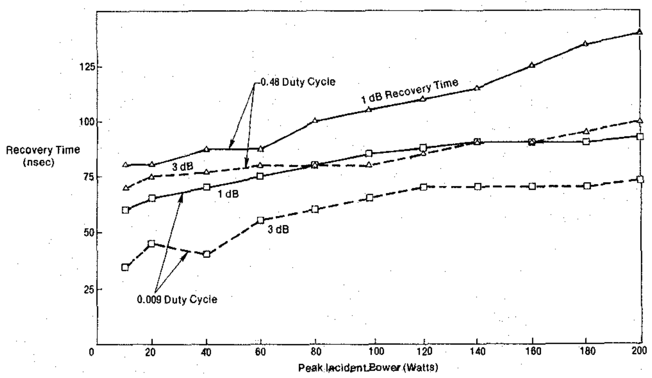

Figure 7. Recovery Time as a Function of Incident Power Over a 500:1 Range of Duty Cycle

The spike and flat leakage for the gated and ungated PIN diode stage is shown in figure 8. The spikewidth is shown to be under 20 nsec and is a result of the fast-acting PN junctions rather than the RF-primed limiter. Spike leakage is under 50 mW peak, and flat leakage is less than 20 mW peak. The (gated) attenuation for the RP at 4 kW peak incident power was measured to be 106 dB within 20 nsec of the arrival of the pulse. Insertion loss and VSWR was under 0.8 dB and 1.40, and the current-controlled attenuator yielded over 70 dB of attenuation.

e. Sensor. The absence of the priming discharge, even for a single pulse, can result in PIN diode burnout. Therefore it is necessary to use a small solid-state sensor 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 and the overall response time of the circuit is 3 μsec.

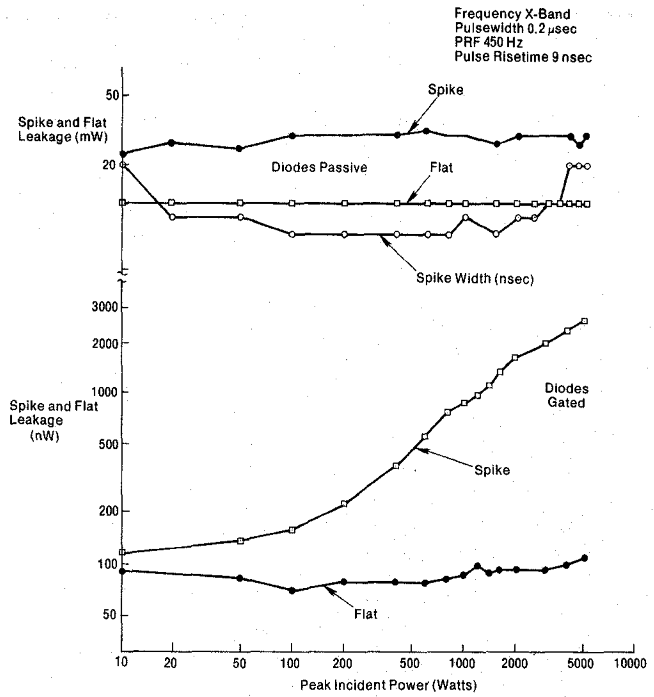

Figure 8. Leakage Characteristics as a Function of Incident Power for Gated and Ungated Diode Modes

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 nsec at average power levels of 100 watts. 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.

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.

References

1. L. Smullin and C. Montgomery, *Microwave Duplexers*, MIT Radiation Laboratory Series, Vol. 14 (New York: McGraw-Hill, 1948).
2. L. Gould, "Improved Keepalive Design for TR Tubes," *Proc. IRE*, Vol. 45, pp. 530-533, April 1957.
3. H. Goldie, "Radioactive (Tritium) Ignitors for Plasma Limiters," *IEEE Trans. on Electron Devices*, Vol. ED-19, No. 8, August 1972, pp. 917-921.