exist in the filter) to insure that there was no conversion to any of the existing modes. Measurements in the TE_{30} and TE_{40} modes were not performed because of lack of suitable transitions for launching and detecting these modes.

The filters have been operated by NASA at passband power levels up to 400-kW CW without exhibiting arcing. Furthermore, the effectiveness of the filters has been demonstrated in that the improvements in X-band receiver noise levels is almost exactly the level indicated by the attenuation curves of Fig. 4 [6]. Thus a truly multimode fourth-harmonic filter operating at 400-kW CW has been demonstrated.

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X-Band High-Power Multipactor Receiver Protector

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***Abstract*—High vacuum devices incorporating the secondary electron resonance phenomenon have been used for several years in receiver protection circuits for high-power high-pulse repetition frequency (PRF) radars. These are known as multipactor devices. Recent technological developments have increased the peak-power handling capability and bandwidth of airborne-qualified devices to 50 kW and 12.5 percent, respectively. Life tests on multipactor devices have demonstrated 2500 h of failure free operation.**

I. Multipactor Phenomenon

A MULTIPACTOR DISCHARGE, or secondary electron resonance, is an electron phenomenon which can occur in a vacuum environment in the presence of microwave power. When the internal device dimensions and the RF voltages are such that electrons can be accelerated from one electrode to another in one half RF cycle, and the electrode surfaces have a secondary emission coefficient greater than unity, the density of electrons between the electrodes is multiplied.

An RF signal with electric field proportional to sin $2\pi ft$ applied across the gap between two electrodes can accelerate an electron in the gap to a velocity sufficient to cause δ secondary electrons to be emitted upon collision with one of the electrodes where δ is the coefficient of secondary emission of the electrode surfaces. If the amplitude of the electric field is such that the transit time across the gap is $1/(2f)$, i.e., one half RF cycle, and an initial electron is at one electrode at the beginning of an RF cycle, the electron will arrive at the other electrode and secondary electrons will be emitted at the same point in time as the RF voltage is changing sign. These secondary electrons are then accelerated back toward the original electrode. At the end of a full RF cycle, $1/f$, δ electrons arrive at the original electrode and δ^2 secondaries are emitted. This simple example leads to the result that the number of electrons in the gap increases by a factor of δ after each half RF cycle. The number of electrons in the gap is given by

$$N = N_0 \delta^{(2tf)} \tag{1}$$

where N equals the number of electrons at time t and N_0 equals the number of electrons at $t=0$ [1].

Electron multiplication according to (1) continues until space charge forces become sufficient to limit the density. The saturated electron volume density has been measured to be 3×10^{10} electrons/cm^3 [1]. Since the volume of a typical 10-GHz multipactor resonator is 10^{-2} cm^3 and if $\delta=5$ and $N_0=1$ are assumed, (1) shows that the multipactor discharge is fully saturated in 0.6 ns.

Once the electron discharge is established, a significant portion of the RF energy is converted into electron kinetic

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energy which is dissipated in the form of thermal energy at the surfaces of the electrodes. The presence of the cloud of electrons within the resonator has a significant detuning effect [1] on the RF impedance causing a portion of the energy to be reflected. The effect of detuning depends on the Q, i.e., high-Q narrow-band resonant circuits are primarily reflective and low-Q broadband circuits are primarily absorbtive.

The threshold at which multipacting begins is the power level necessary to accelerate an electron between electrodes in a one half RF cycle. It has been shown theoretically [2] and experimentally [3], [4] that the discharge within a fixed gap resonator can occur at a range of power levels above the threshold. For any power level within this range the output power is limited to the threshold value. Above the multipacting range the accelerated electrons cross between electrodes in less than one half cycle and resonance is destroyed; below the threshold the electrons have insufficient energy to cross the gap and no multiplication occurs.

II. Multipactor Receiver Protector

The multipactor phenomenon described above performs the basic function of a microwave limiter. In order to develop a multipactor limiter for a high PRF radar system several problems had to be addressed. The bandwidth and dynamic range of high-Q single-resonator multipactors had to be increased. A technique for maintaining the high coefficient of secondary emission on resonator surfaces throughout the life of the device had to be developed and limiting on the first RF pulse had to be insured.

Initial work on experimental multipactor limiters incorporated single resonator gaps [1]. These devices were limited in instantaneous bandwidth (2.5 percent) and achieved large dynamic range only by mechanical tuning. Devices developed in the mid-1960's at the Hughes Aircraft Company, Microwave Tube Division demonstrated instantaneous bandwidths of 8.5 percent. This was achieved by incorporating a RF circuit which consisted of several coupled low-Q resonators. This type of circuit is known as a comb-line filter and is shown schematically in Fig. 1. This type of filter lends itself very easily to multiple resonator gap spacings. The spacings were chosen in such a way that multipacting ranges overlapped thereby increasing the dynamic range of the device to 20 dB without mechanical tuning.

An essential requirement for any multipactor device to function is that the surfaces of the resonators have a secondary emission coefficient greater than unity. This characteristic is generally not found in metals, but is common for metal oxides, such as magnesium oxide (MgO). However, MgO has the undesirable property that it tends to reduce to elementary magnesium when subjected to electron bombardment. In order to insure long life in an operational multipactor device, the vacuum environment of the device must be maintained with a background partial pressure of primarily oxygen, thus maintaining the secondary emission material (SEM) in an oxidized state. This is achieved by incorporating a silver oxygen leak tube as part of the vacuum envelope and a small integral ion pump to maintain the necessary vacuum pressure.

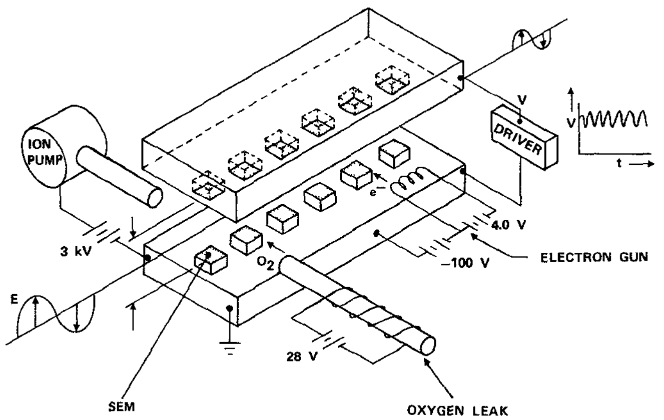

Fig. 1. Schematic drawing of a multipactor device.

There is one additional feature which is essential for a multipactor device to operate effectively as a receiver protector. This necessary component is an electron source which insures that there are always electrons within the resonator gaps, so that when the first RF pulse is applied, limiting begins in the first RF half cycle. Without an electron source the first few RF pulses would not be limited and the receiver would be damaged. The Hughes multipactor limiters incorporate a simple electron gun as an electron source. This and the other major features are illustrated schematically in Fig. 1.

III. 8714H High-Power Multipactor Limiter

At the time this effort was begun the state-of-the-art in airborne-qualified multipactor limiters at X-band was 500-W peak 250-W average input-power handling capability with an 8.5-percent instantaneous bandwidth. The objective of the program was to improve the peak- and average-power handling capability and increase the bandwidth while improving the manufacturing technology of multipactors in general. The new multipactor limiter was to be integrated with a low-level solid-state limiter to produce a complete receiver protection package. A summary of the performance characteristics of this integrated limiter package is shown in Table I. A photograph of the device is shown in Fig. 2.

The improved power handling capability and bandwidth of the 8714H was achieved by improvements in the comb-line filter. An overlapping multipactor range approach was used and the final design included seven separate multipacting resonators with five different gap spacings. Particular effort was expended in tuning the individual resonators to achieve the increased bandwidth.

A characteristic of the multipactor limiter is the extremely constant output, or "flat leakage" power in the

TABLE I
HUGHES MODEL 8714H—HIGH-POWER MULTIPACTOR LIMITER WITH LOW-POWER SOLID-STATE LIMITER

Center Frequency	=	9.6 GHz
Bandwidth	=	12.5%
Maximum Peak Input Power	=	50 kW
Maximum Average Input Power	=	500 W
Duty	=	1%
Flat Leakage Power	≤	50 mW
Isolation (at 50 kW)	≥	60 dB
Spike Leakage Power	=	0.05 ERG
VSWR	=	1.6:1.0
Insertion Loss (Cold)	=	1.5 dB
Recovery Time	<	15 nanoseconds

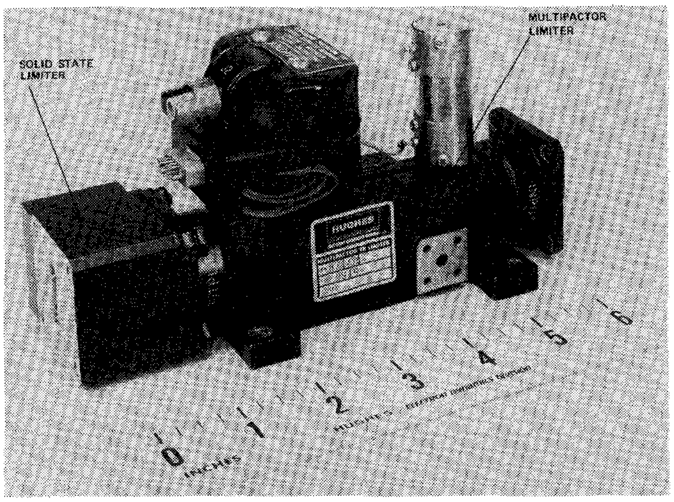

Fig. 2. 8714H multipactor limiter with solid-state limiter.

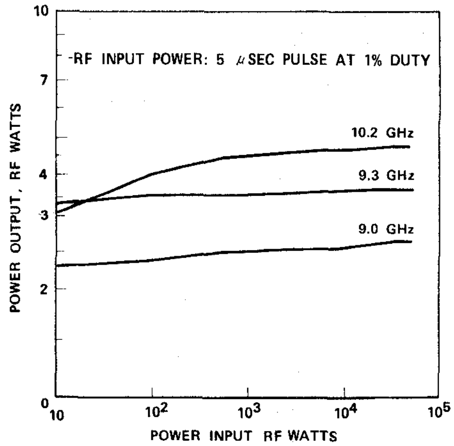

Fig. 3. P_{out} versus P_{in} for the multipactor stage.

multipacting range. This is shown in the plot of power output P_{out} versus power input P_{in} in Fig. 3. The data also shows that isolation and dynamic range in excess of 40 dB were achieved by the multipactor without a solid-state limiter. When the multipactor and a solid-state limiter were integrated, these parameters were increased to 60 dB.

In addition to the 50 kW at 1-percent duty continuous performance, the device was successfully operated at 6-kW peak at 50-percent duty for several minutes.

The solid-state limiter used in the system was manufactured by Microdynamics, Inc., Woburn, MA. It accounted for approximately 0.5 dB of insertion loss and was designed to limit from 15-W peak to 50-mW peak. The remaining 1.0 dB of insertion loss was contributed by the multipactor. The recovery time of less than 15 ns was demonstrated by the solid-state limiter and no change was noted when the multipactor was added to the circuit. This confirmed the extremely fast recovery time expected from theory.

IV. CONCLUSION

The technology for fabricating multipactor limiters has advanced to the point where fully airborne-qualified multipactor limiters now exist which meet the receiver protection requirements of even the highest power high PRF *X*-band radar system. Peak powers of 50 kW and average powers of 500 W can be limited and average powers up to 3 kW can be handled for short periods of time. The devices exhibit the extremely fast nanoseconds range recovery times characteristic of previous multipactor limiters. Well controlled testing has demonstrated lifetimes in excess of 2500 h.

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