HIGH-POWER MIC DIODE LIMITERS FOR S- AND X-BAND RADARS

Shigekazu Hori, Masahiro Kuroda, Kenji Kanema
and Susumu Okano

Toshiba Research and Development Center
Toshiba Corporation
1 Komukai-Toshiba, Saiwai-ku,
Kawasaki 210, Japan

ABSTRACT

S- and X-band passive MIC diode limiters have been developed for high power applications. Two PIN diodes with I layer thickness of 9.5μm and 1.5μm are shunt-mounted to 50 ohm microstrip lines. The limiters can handle 2-kW peak input power with less than 100mW peak leakage power for pulsed RF signals of 1μs width and 0.1 percent duty ratio.

Introduction

High-power waveguide diode limiters are being used for radar receiver protection.(1) MIC diode limiters are, however, most desirable for applications such as in active phased-array radar modules, in which small size and light weight are indispensable. This paper reports on newly developed 2-kW S- and X-band MIC limiters by using optimized Si PIN diodes and a novel technique for preventing RF discharge on microstrip lines. Observed discontinuities in limiting characteristics are discussed on a basis of measured large-signal diode impedance.

Limiter Circuit Configuration

Fig.1 shows a circuit configuration of the developed two-stage MIC diode limiter and Fig.2 shows its equivalent circuit. PIN diode chips D1 and D2 are shunt-mounted to 50-Ω microstrip lines fabricated on a 0.635mm thick alumina substrate. Each diode chip, mounted on a pedestal by using Au-Si eutectic solder, is connected to the microstrip lines with Au wires of 25μm diameter. The pedestals are attached to the rear side of alumina substrate by using Au-Sn eutectic solder. A DC return circuit is provided via a 100-Ω quarter wavelength microstrip line.

The diode junctions are coated with silicone rubber. The microstrip line of the input-port side is also conformally coated with silicone rubber so as to avoid corona discharge at microstrip line edges. This has been found to be a very effective technique for discharge suppression with little sacrifice of insertion loss and VSWR. Unless silicone rubber was coated, the microstrip line could not withstand above 1kW peak power.

Si PIN Diodes

Diode wafers were fabricated by p-type diffusion on-to I-layer, which was epitaxially grown on highly-doped n^+ substrate. Actually, the I-layer is an undoped n-type layer with electron concentration of $2 \times 10^{13} \sim 2 \times 10^{14} cm^{-3}$ depending on the layer width. After completing Ti-Pt-Au metallization on the p-type side, the wafers were etched into mesas.

In order to determine optimum I-layer width W_I of the diodes for the two-stage limiter, diodes with W_I = 1.5, 5.5, 9.5 and 13.6 μm were made, and their limiting characteristics were measured in a single-stage microstrip circuit for pulsed RF power up to 3kW at 3 GHz (Figure 3). From circuit design considerations described later in the next section, each diode was fabricated to have nearly the same value of junction capacitance C_j by adjusting its junction area. It can be seen from Figure 3 that diodes with narrower W_I give less leakage power, and each diode with $W_I \geqq 5.5$ μm exhibits a discontinuous decrease of leakage power at each specific RF input power. This discontinuity in limiting characteristics was found to be always accompanied by a discontinuous increase in rectified diode current.

These discontinuities have not been disscussed in computer simulation(2) on large signal behaviors of PIN diodes. In order to get insights into the discontinuity, large-signal diode impedance was measured as a function of CW RF input power, P_{in}, up to 43dBm using a network analyzer. The measured impedance loci (P_{in}-Z loci) are shown by dashed lines in Fig.4 for diode A (W_I = 1.5μm) and B (W_I = 9.5μm), where measured small-signal diode impedance loci (V_D-Z loci) are also shown by solid lines with forward bias voltage V_D as a parameter. The P_{in}-Z locus and V_D-Z locus of diode A or B can be seen to follow nearly the same curve, suggesting that in Si PIN diodes, a DC carrier injection has an essentially similar effect on diode impedance as RF carrier injection. Hence, it is reasonable to assume that, for P_{in} > 43dBm, diode B's P_{in}-Z locus will follow its V_D-Z locus. Then, the limiting characteristics discontinuity observed in diode B but not in diode A (see Figure 2) can be understood as follows. Contrary to diode A's P_{in}-Z locus lying on an almost constant reflection coefficient circle, diode B's locus passed through near the center of the Smith chart. This means that RF power dissipation is abruptly accelerated in diode B due to power absorption when P_{in} drives diode B's impedance near the Smith chart center. The dissipated power gives rise to a rapid increase of carrier injection into the I-layer, which, in turn, changes the RF impedance state of the diode regeneratively.

Waveforms of leakage power (P_L) and rectified current (I_R) were measured for diode B at this specific input power (P_S) at which this discontinuous limiting occurs. Fig.5 shows the waveform of P_L and I_R at the point of P_S = 52dBm marked by X in figure 3. In the fore-half of RF pulse, leakage power is about 30W and little rectified current flows. However, in the later half of RF pulse, leakage power greatly diminishes and much rectified current begins to flow. With a little further increase of input power beyond P_S, leakage power is only observed as a spike waveform at the front edge of RF pulse.

These discontinuities may also arise from the junction temperature rise of diodes due to RF heating. Junction temperature was measured by a forward voltage drop method.(3) RF pulse and successive DC pulse with

1μs pulse width was applied to a diode with $W_I = 9.5\mu m$. Peak junction temperature was measured to be about 125 °C at input power of 52dBm, and forward junction voltage at forward bias current of 50mA decreased from 0.95V at room temperature to 0.83V at the above input power. This increment of junction temperature during RF pulse will help to increase carrier injection into I-layer and will cause the discontinuity.

MIC Limiter

The developed S- and X-band limiters have a two stage configuration, and the inside view of the S-band limiter is shown in Fig.6. The housing is hermetically sealed using conductive silicone rubber. Diodes with I-layer width W_I = 9.5μm and 1.5μm have been used for first and second-stage diodes D1 and D2, respectively. The effective electrical length between D1 and D2 was made nearly equal to 90° for the S-band limiter and 270° for the X-band limiter by compensating for bonding-wire inductance L_B. Junction capacitances of the two diodes were determined using CAD in order to realize low insertion loss and VSWR. The optimized junction capacitance to satisfy VSWR $\leq$ 1.2 was 0.32 ~ 0.42 pF for the S-band limiter and 0.25 ~ 0.30 pF for the X-band limiter.

At small signal input power, the insertion loss is less than 0.8dB and 1.2dB for S-band and X-band limiters, respectively, and VSWR is less than 1.2 for both limiters.

Figure 7 shows the limiting characteristics of the S-band and X-band limiter for pulsed RF input power of 1μs width and 0.1 percent duty ratio. The averaged peak leakage power is less than 100mW peak in both limiters for RF input power up to 64dBm.

There can be seen a small discontinuity in limiting characteristics at $P_{in} \simeq$ 43dBm for both limiters. This corresponds to the discontinuity associated with diode D1 (W_I = 9.5μm), which, in a single-stage configuration, shows discontinuity at P_{in} = 52dBm as shown in Fig.3. The difference of ~ 10dBm power level can be considered as follows. In a two-stage limiter, diode D2, due to its thinner I-layer, changes or fires to the low impedance state at lesser input power than D1. After the firing of diode D2, the RF voltage at D1 becomes almost twice because of 90° or 270° electrical length between the two diodes. Hence, diode D1 can change to the low impedance state at 6dB less input power than in a single stage limiter.

The spike leakage was measured to be 180mW peak with 9ns width for the S-band limiter. Fig.8 shows a detected leakage power waveform of the S-band limiter at input power of 2kW peak. The waveform was measured by a crystal detector (HP-423A) and a sampling oscilloscope. Peak power and pulse width of the narrow spike leakage are calibrated values by compensating for the effect of C-R time constant of the detector.

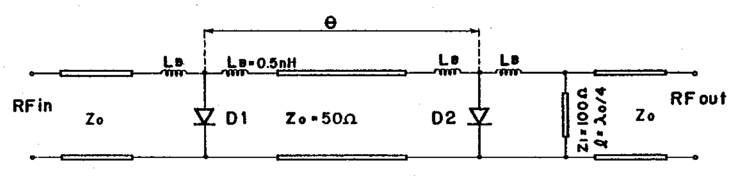

Fig.2 Equivalent circuit of diode limiter

Meanwhile, no spike leakage was observed for the X-band limiter. This difference might be explained by the dependence of carrier storage rate on frequency. Carriers injected at forward RF cycle are not completely depleted at reverse RF cycle, and the carriers are stored in every forward RF cycle until a steady-state condition is established. The time required to reach the steady state might be shorter for X-band frequency than S-band frequency, and, hence, the spike leakage has not been observed on X-band limiter.

Both limiters can withstand for 4kW peak for a short time period. The MTTF (Mean-Time-To-Failure) of these limiters are estimated from RF life tests to be about 20,000 hours for an input power of 2kW peak.

Conclusion

High power passive MIC diode limiters at S- and X-band have been developed using two Si PIN diodes with different I-layer width. The limiters can handle 2kW peak pulse RF power of 1μs pulse width and 0.1 percent duty ratio. The averaged peak leakage power was less than 100mW. The discontinuity observed in the limiting characteristics of diodes with thick I-layer width ($\geq$ 5μm) has been discussed in terms of large-signal diode impedance. Conformal coating of silicone rubber on the microstrip line has been found to be very effective for prevention of corona discharge.

Acknowledgement

The authers wish to thank M. Kurata, M. Ohtomo, M. Kihara and M. Higashiura for their many valuable discussions and T. Anegawa for technical assistance.

References

1. W.F. Krupke et al., "Solid State X-Band Power Limiter", IRE Trans. on Microwave Theory and Techniques, vol. MTT-9, pp. 472-480, November, 1961.
2. M.Kurata, "A Computer Study of Power-Limiter Diode Behavior", Solid-State Electronics, vol. 17, No.9, pp. 951-961, September, 1974.
3. J.F. White, "Semiconductor Control", Artech House, Inc. Massachusetts, 1977, pp. 104-114.

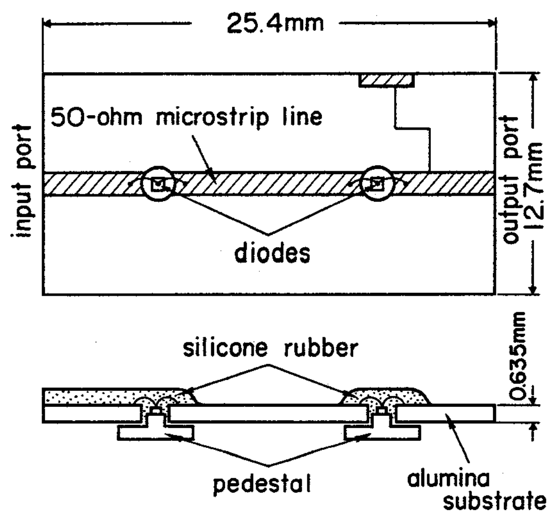

Fig.1 Circuit configuration of MIC diode limiter

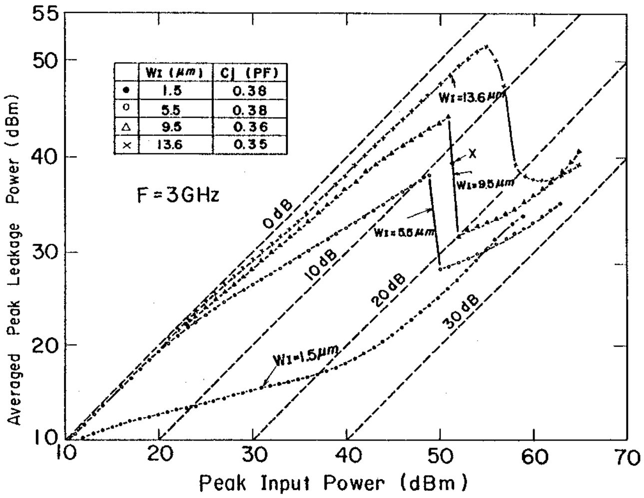

Fig.3 Limiting characteristics of Si PIN diodes with different I-layer width
RF pulse: 1μs width, 0.1 percent duty ratio

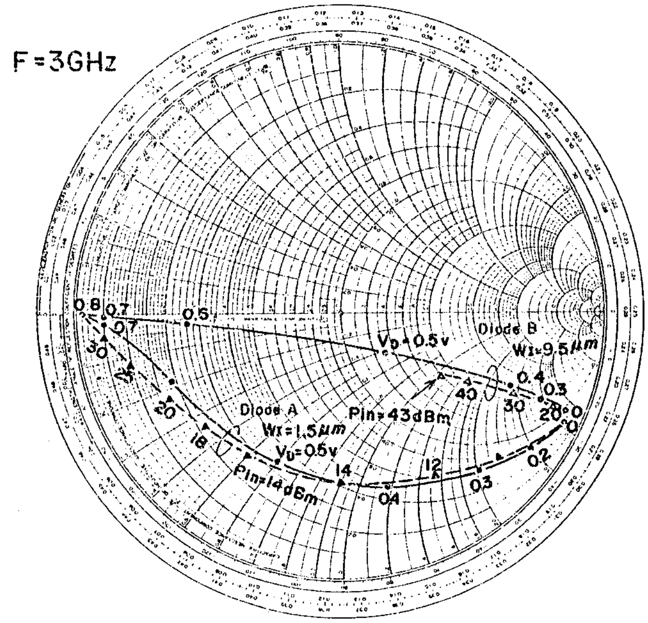

Fig.4 Measured large-signal impedance loci (dashed lines) and small-signal impedance loci (solid lines) for diode A and B

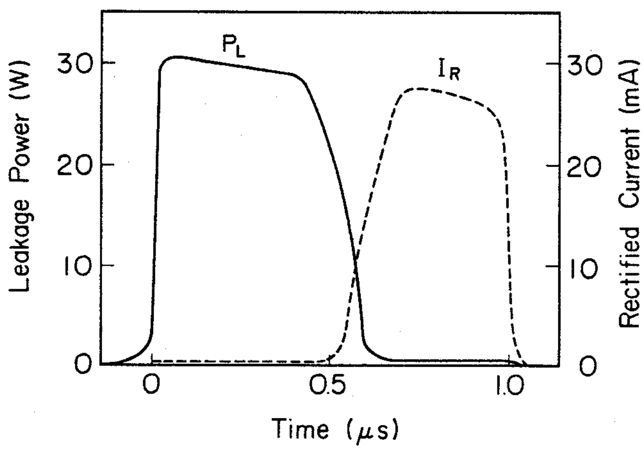

Fig.5 Leakage power (P_L) and rectified current (I_R) waveforms of a single-stage diode limiter at the input power of 52dBm noted X in Fig.3.

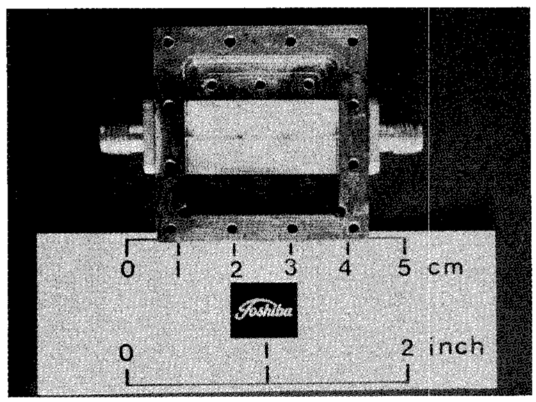

Fig.6 Inside view of hermetically sealed S-band limiter

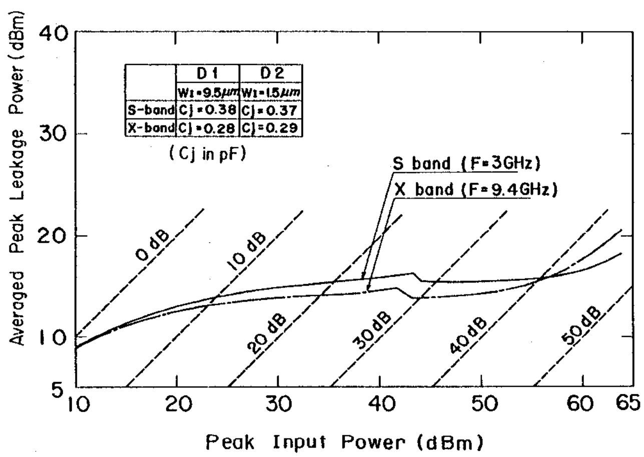

Fig.7 Limiting characteristics of S-band and X-band limiters for pulsed RF input power of 1μs width and 0.1 percent duty ratio

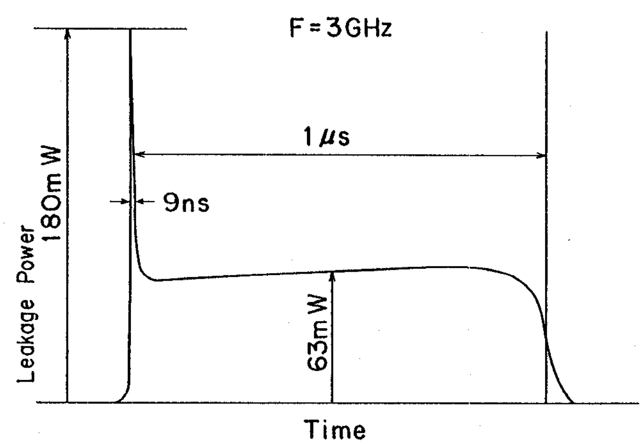

Fig.8 Detected RF leakage waveform of S-band limiter at pulsed RF input power of 2-kW