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A Cryogenically Coolable Microwave Limiter

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A microwave (ca. 3 GHz) limiter, constructed using a GaAs PIN diode and microstrip impedance transformation circuit, limited 300-ns long 11-W microwave pulses to 70 mW at ca. 4.2 K. This limiter was implemented in a pulsed electron paramagnetic resonance (EPR) spectrometer to protect a low-noise microwave preamplifier from the high-power pulses. © 1999 Academic Press

INTRODUCTION

Many EPR experiments are conducted at cryogenic temperatures. This is especially true of most studies of metals in biological systems. Since increased signal-to-noise (S/N) is a dominant need for most applications of EPR, spectrometer design goals include (a) cooling to as low a temperature as practical all components that contribute thermal noise to the final spectrum, and (b) minimizing the loss between the signal source and the first-stage microwave amplifier. For pulsed EPR measurements, using a reflection type resonator, at least at X-band and lower frequencies, it is necessary to have a limiter prior to the low-noise microwave preamplifier in order to prevent damage to the amplifier. The limiter insertion loss results in increased noise figure for the detection system, but this is unavoidable with a reflection resonator spectrometer system. However, the net insertion loss will be minimized, and the S/N of the spectrum will be maximized, if the limiter and preamplifier are cooled to as low a temperature as is practical. Usually, this would mean a temperature close to that of the sample and resonator. This is the incentive for constructing a cryogenically coolable limiter.

There are advantages to measuring some EPR parameters at S-band (2–4 GHz), because some hyperfine structure is better resolved at S-band than at X-band (ca. 9 GHz) (*1*), and because electron spin echo envelope modulation (ESEEM) is deeper at S-band than at X-band (*2*). Consequently, this paper focuses on an S-band implementation, but the approach presented can be extended to higher or lower frequencies.

A PIN diode can be used as a high-speed microwave switch by controlling its on and off states either by an applied dc bias or by rectification of a portion of the microwave signal (*3*). A passive limiter utilizes the power of the input pulse to bias a PIN diode into conduction. When the diode is connected in parallel with the transmission line, the conducting diode acts like a closed switch, which effectively shorts the transmission line and reflects most of the incoming power. Commercial passive limiters are available for a wide range of frequencies. However, they use silicon PIN diodes that will not function at cryogenic temperatures in the liquid helium range. GaAs PIN diodes will work at 4 K.

Whether or not a semiconductor device will work at cryogenic temperatures is dependent on the type of semiconductor, dopant and the level of doping, and the charge carrier mechanism used in the device. Freeze-out occurs when the thermal energy is lower than the ionization energies of donors or acceptors. While most silicon devices cease to perform below liquid nitrogen temperatures, the ionization energy for GaAs, at the high dopant levels used in PIN diodes, is very low and freeze-out does not occur even at 4 K (*4*).

Until recently, GaAs PIN diodes have not been used in limiters. It is difficult to generate self bias for GaAs PIN diodes from the input microwave power pulse. Self-biasing is caused by rectification that takes place at the diode junction and provides the dc current to keep the diode in a conducting state. It was shown by Leenov (*5*) that the rectification effect is dependent on the ac-controlled intrinsic-layer resistance relative to the characteristic impedance of the transmission line. Therefore, a high characteristic impedance level should enhance the rectification action. The design approach was to use an impedance-transforming section to increase the characteristic impedance of the transmission line at the location of the PIN diodes. The high impedance will also produce high isolation with low conduction in the diode.

DESIGN OF THE COOLABLE LIMITER

The limiter described in this paper utilized symmetric second-order Chebyschev multisection impedance matching transformers (*6*), implemented by selecting the widths of the copper traces and the dielectric of the board, to change the impedance level from 50 to 100 Ω where the limiter diodes were located and back to 50 Ω at the output of the limiter. The schematic diagrams for this limiter is given in Fig. 1 (it is quite different from the circuit used in commercial limiters utilizing

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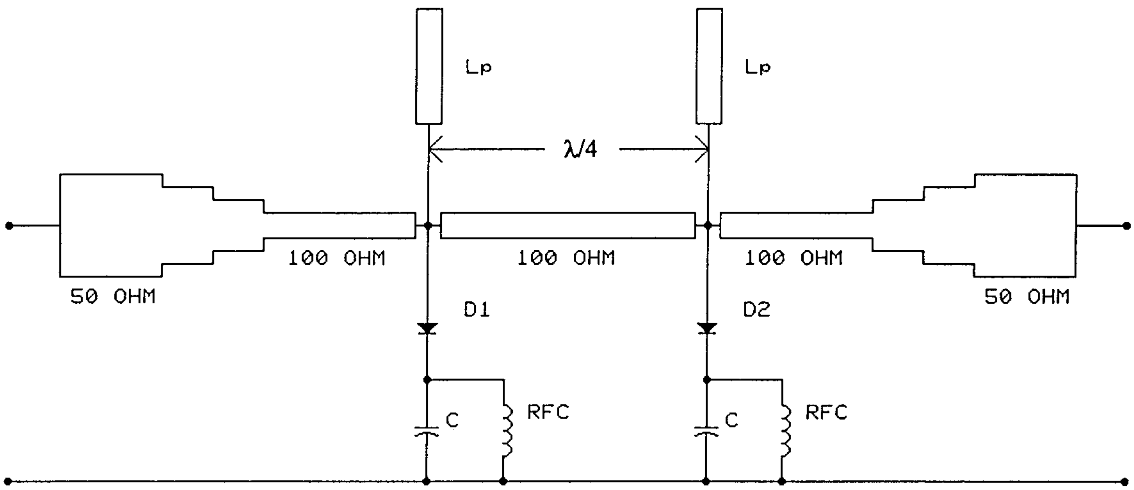

FIG. 1. Limiter micro strip circuit, including impedance matching and bias circuits. Design frequency 2 to 4 GHz (by simulation using EEsof). Line widths (W) and lengths in mm are: W = 1.84, L = 12.0 (50 Ω); W = 1.31, L = 12.2 (step 1); W = 0.605, L = 12.5 (step 2); W = 0.351, L = 12.6 (100 Ω); W = 1.84, L = 22.0 (L_p). C = 10 pF. RFC is a RF-choke to provide a dc path for diode bias current. It consists of a 13-turn helix of No. 44 copper wire and is approximately 0.76 mm in diameter and 1 mm long.

Si devices). The design was facilitated by the use of the EEsof microwave circuit development software from Hewlett Packard.

Two GaAs PIN diodes were spaced a quarter wavelength apart, with dimensions chosen for 3 GHz, the center of our design range of 2–4 GHz. The quarter wavelength spacing minimizes the reflections when the diodes are not conducting, thereby improving the standing wave ratio and insertion loss for this condition. It also provides the maximum reflection when the diodes are conducting, thereby improving the isolation. The second diode is smaller than the first and has a lower total capacitance. This allows the first larger diode to reflect the main pulse while the second, faster acting diode helps reduce the short power spike passed by the slower first diode.

For the off state, the equivalent circuit of the diode is a parallel conductance and capacitance. The conductance is the low, nonconducting value for the diode, and the capacitance is due to the parallel combination of the diode junction and case capacitance. The inductance, L_p, parallel resonates the capacitance at the design frequency which minimizes insertion loss for the nonlimiting state. For the on state, the equivalent circuit of the diode is a series resistor and inductance. The resistor is the low, conducting state value for the diode and the inductance is due to the bonding lead from the case to the diode. The capacitor, C, series resonates the inductance at the design frequency and maximizes isolation for the limiting state. The RF-choke (RFC in Fig. 1) provides a dc path for the diode bias current.

The GaAs PIN diodes were type MP6004 manufactured by Microwave Device Technology Corp. (Westford, MA). The two diodes, D1 and D2, had a nominal junction capacitance of 1.3 and 0.06 pF, respectively. The 10-pF capacitors are high-Q, planar, microwave capacitors from Johanson Dielectrics (Burbank, CA). The microwave board is 0.050 inch (1 inch = 25.4 mm) Rogers TMM-6. The limiter was enclosed in a copper box with sma input and output connectors to facilitate modular testing.

An alternative design could use a constant bias voltage to assist in turning the diode on and off, but we did not find this any more effective than the impedance transformation. Another approach would be to switch the diode with a pulsed signal synchronized to the microwave pulse. However, from a system design perspective, a totally passive limiter is much safer than an active limiter.

LIMITER TEST RESULTS

As a first check on the behavior of the GaAs PIN diodes, a conventional 50 Ohm micro strip design was fabricated and tested to verify the criteria concerning limiting level and turn on characteristics of the limiter diodes. As predicted, there was little or no limiting action at room temperature even for relatively high power levels. However, at 4 K the device began to function as a limiter, indicating that the characteristics of the GaAs PIN diodes were more favorable to self-biasing at cryogenic temperatures even when used on a 50-Ω line.

Next, the GaAs PIN diodes were used in the impedance transformation circuit described above. This limiter was tested at room temperature and at 4.2 K using a liquid helium cooled cryostat. A 300-ns pulse of power at the center design frequency of 3 GHz was used for the input. The input power level was calibrated by use of a microwave power meter, and the output power pulse was measured by a calibrated crystal detector. Figure 2a shows the performance characteristics of the limiter at room temperature. At 300 mW there was not sufficient power to cause the diodes to conduct, and the pulse was

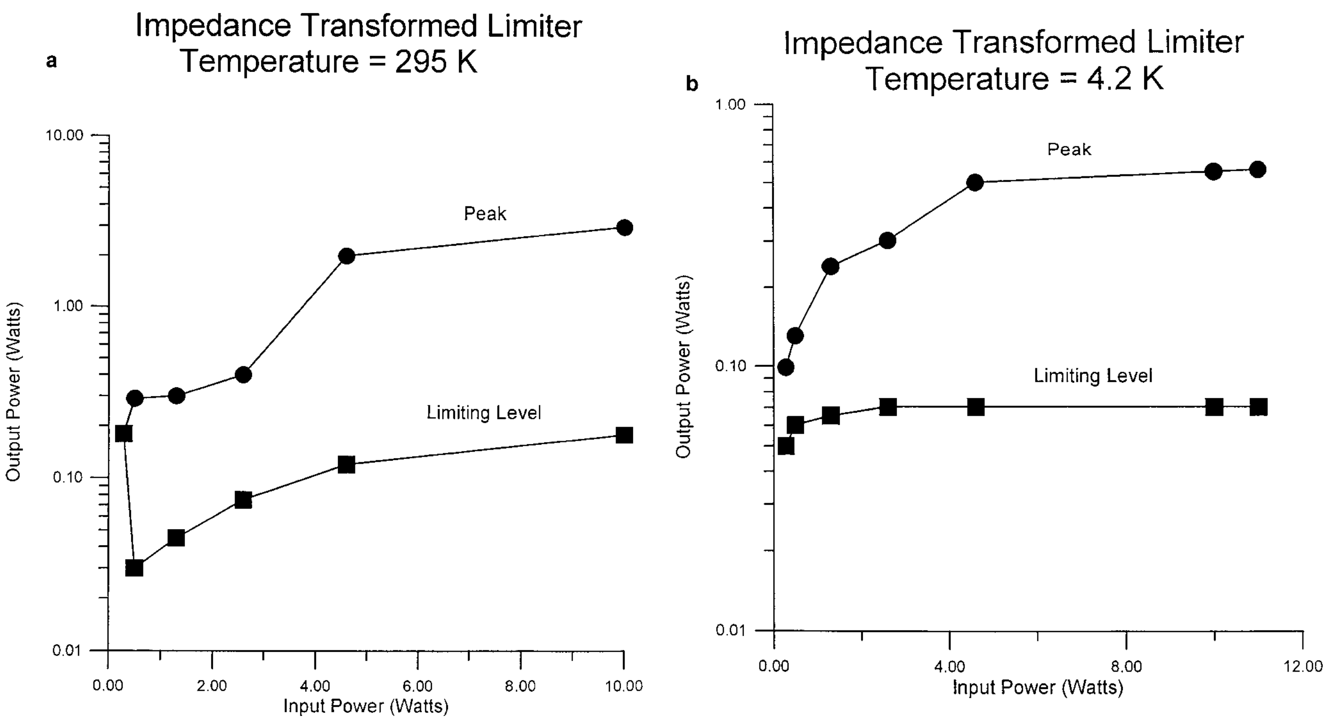

FIG. 2. Limiting behavior of (a) the new GaAs PIN diode limiter at room temperature and (b) the new GaAs PIN diode limiter at ca. 4.2 K temperature.

attenuated only by the insertion loss of the limiter. For higher power levels the diodes reduced the pulse power to about 30 mW for an input pulse of 0.5 W and to less than 180 mW up to 10 W input power (the highest available for test). During the time the diode is responding to the incident microwave pulse, some power gets through the limiter. This is called "spike leakage." A common specification for spike leakage is ca. 0.1 erg and is measured as the product of the power (in watts) that leaks through times the width of this spike at the 3-dB points in ns times 10^7 to get ergs. Recovery time is measured to the 1-dB loss point. Figure 2a shows that the spike power was relatively large and reached 3 W for 10 W input power. The width of the spike was approximately 20 to 40 ns, which corresponds to ca. 0.9 erg spike leakage. These results verify the original assumption that GaAs PIN diodes would function as limiters on a transmission line with a sufficiently high characteristic impedance.

Figure 2b shows the output power for the limiter at a temperature of ca. 4.2 K, when cooled by He gas flow in a Cryo Industries (Atkinson, NH) cryostat. The limiting level in this case exhibits nearly ideal characteristics, being essentially flat at 70 mW for input power of 2 to 11 W. The peak power of the initial power spikes is reduced nearly an order of magnitude for the cooled limiter compared to that at room temperature. In addition, the spikes were much shorter, with pulse power not exceeding 200 mW for more than 10 ns, corresponding to ca. 0.02 erg spike leakage. Our tests show that the turn-on characteristics of GaAs PIN diodes are much sharper at cryogenic temperatures, making the GaAs PIN device more effective as a limiter at low temperature than at room temperature.

The impedance transformed limiter was used to perform S-band electron spin echo (ESE) measurements at cryogenic temperatures. The recovery time of the limiter was short enough that it did not increase the spectrometer dead time beyond that observed when a room temperature silicon limiter was used in the spectrometer. The recovery time of the limiter from the flat leakage value to baseline was less than 20 ns, as judged from the shape digitized by a LeCroy oscilloscope. While the spike-limiting characteristics of the impedance transformed limiter at room temperature are not ideal, the limiter is usable for ESE at room temperature. Presumably, the input stage of the amplifier saturates during the very short spikes, acting as a low-level limiter. We used this limiter at room temperature for extensive characterization of the S-band spin echo amplitude and noise performance (*7*).

The insertion loss of the limiter was measured, at room temperature, at the design center frequency of 3 GHz to be 1.3 dB. This is somewhat higher than the insertion loss of the commercial room temperature device. This is primarily due to the octave design bandwidth (2–4 GHz). The insertion loss measured as a function of frequency was less than 2.5 dB from 2.5 to 3.4 GHz. The minimum insertion loss was 0.85 dB at 2.8 GHz. A design with narrower band width should decrease the insertion loss near the center frequency. Since the limiter consists only of passive devices, the noise figure of the limiter is the same as that produced by any loss element, such as a

TABLE 1
Noise Parameters for the Coolable Limiter

Temperature (K)	T_e (K)	NF (dB)
290	101	1.3
77	27	0.39
4	1.4	0.02

length of coaxial cable. The effective noise temperature is given by

$$T_e = T(l_a - 1), \quad [1]$$

where T is the physical temperature and l_a is the insertion loss of the limiter (ratio of the input power to the output power).

The noise figure (NF) in dB is given by

$$\mathrm{NF} = 10 \log\left(1 + \frac{T_e}{T_0}\right), \quad [2]$$

where $T_0 = 290$ K.

Based on a measured insertion loss of 1.35 (1.3 dB), the noise parameters of the coolable limiter are given in Table 1 for three temperatures.

The results of the limiter leakage tests using a microstrip stepped impedance transformer show that for an impedance ratio of 50:100, the GaAs PIN diodes function well as limiters, while the limiting action was quite poor for the case without impedance transformation. It is predicted that better limiter performance can be obtained with a somewhat higher impedance transformation ratio, using a faster diode, and/or a reduction of the bandwidth, and would provide limiting characteristics equivalent to a commercial noncoolable device at room temperature and even better characteristics when cooled.

For comparison, commercial limiters generally are designed for microwave pulses of less than 1 μs, 0.1% duty cycle, ca. 0.8 dB insertion loss in the S band, and ca. 20 dBm (100 mW) "flat" (CW) leakage. Specifications vary depending on power handling ability, frequency range, and recovery time.

We learned following the completion of this work, that Watkins–Johnson Company (Palo Alto, CA) began marketing GaAs MMIC chip limiters for the 1–12 GHz range, with a pulse power limit of +23 dBm for 10 μs, and 4 dB insertion loss.

CONCLUSION

The cooled GaAs limiter has limiting characteristics comparable to that of conventional room temperature silicon PIN diode limiters. The GaAs PIN diode limiter operating at liquid helium temperatures makes possible a whole new approach to biomedical pulsed EPR spectroscopy, by permitting the resonator, limiter, and microwave preamplifier to be cooled along with the sample, thus establishing the lowest possible noise floor for the EPR measurements.

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