An Investigation of PIN Diode Failure Related to High Peak Power

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Introduction
PIN diodes are widely employed as voltage controlled switches to decouple MR receiving loops during the B1 RF excitation phase, where the diode is forward biased "on" introducing an inductor parallel resonant with a loop capacitor (L2 & C2 in Figure 1). The parallel resonant "trap" creates a virtual open circuit in the loop, limiting induced current and thus B1 distortion and SAR to acceptable levels.

Measurements at high RF power levels are difficult at best, so some estimations are necessary. Since almost all of the B1 induced EMF V falls across the trap, the RF current circulating in the trap is given by V/X, X = wL = 1/(ωC), which can be up to 7A peak for very large loop areas. A UM9701 PIN diode has a series resistance of about 0.5Ω at RF, so peak diode power dissipation is on the order of 25W. For most pulse sequences, RF excitation duty cycle is less than 10%, so average diode power dissipation is typically well below the 2.5W maximum rating for the UM9701.

Problem
Diode failures due to excess average power are frequently accompanied by noticeable blackening of the enamel coating on inductors and even desoldered components. However, recently a coil design with large loop areas has had consistent diode failures with absolutely no signs of excess average power. The failures occur quickly when high peak power scans are used. These observations have led to the discovery of a diode failure mode involving brief reverse bias "spikes", a phenomenon that has not yet been published to the authors' knowledge.

Methods and Observations
A SPICE simulation of Figure 1 using a standard PIN diode model (1) illustrates the spiking effect and its apparent cause. Voltage source V1, given a gradual rise by V2, simulates the induced EMF in a loop. Simulation results in Figure 2 indicate that the spiking phenomenon begins at a critical threshold level of V2. The voltage spike across L2 must be the result of a sudden change in the current through D3 and L2 since V(L) = L(di/dt). Since C2 impedes any sudden voltage change, almost all of the spike falls across D3 in a reverse bias sense. Note that the instantaneous diode current (I(D3)) can normally go negative every cycle but that the DC average is always positive. However it appears that when the instantaneous negative current reaches a high enough level, the PN junction becomes unbiased, and I(D3) falls to zero causing L2 to respond with a voltage spike. If the DC forward bias current is increased, a higher instantaneous current level must be reached to cause spiking. It is important to note that an accurate large-signal SPICE diode model was not available for the UM9701, which probably accounts for the much lower voltage and current levels than those encountered in practice using the UM9701.

A test circuit similar to Figure 1 was inductively coupled to a pulsed 1000W RF power amplifier to create the induced EMF. Observations using a 1Gsample/s digital scope confirm the existence and location of spikes in Figure 2, just before the diode current returns to zero. Due to measurement equipment limitations, it is difficult to confirm the exact level and duration of the spikes, but they can be seen repeatably and diode failure is imminent when they begin to occur, indicating that they exceed the 100V reverse breakdown level of a 9701.

An initial indirect observation, which led to the detailed investigation of spiking, showed that the positive voltage drop across the diode (after lowpass filtering) will go negative on the order of volts during RF excitation as the peak RF power is increased and/or the nominal DC bias current is decreased. In Figure 2, the DC bias current (I(R5)) begins to rise at the onset of spiking, indicating a negative trend in the lowpass filtered diode voltage (not plotted). Further experimentation showed that lower DC bias source resistance (<5Ω) can reduce or eliminate spiking for a given bias current. Simulations also show that the DC bias source resistance R5, has a similar effect on spiking while maintaining a constant bias current.

Discussion
Although difficult to observe directly and accurately, the reverse bias diode spikes described herein are validated by simulations, indirect observations, and repeatable diode failure at low average power. Major discrepancies with SPICE simulations are not surprising since available diode models are intended for small signal analysis. While the intrinsic causes of the spikes is still not fully understood, it seems they can be prevented by providing a low impedance DC path across the diode to shunt any negative voltage buildup. For this reason passive traps using anti-parallel Schottky diodes apparently do not fail due to spiking, but this configuration precludes active reverse biasing for high off resistance. As high power pulse sequences increase in popularity, diode failure due to reverse bias spikes will become a serious issue in RF coil design.

References