Electrothermal Modeling of PIN Diode Protection Circuits in MRI Surface Coils

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***Abstract* — A study of the temperature rise in MRI coil PIN diode protection circuits is presented. The study is based on a previously defined electrothermal model for the PIN diode that is applied to MR surface coils. The model shows a rapid rise in the PIN diode temperature with application of the MR transmit pulse and for low duty cycle MR pulse sequences, the diode cools significantly during the off-phase of the MR transmit pulse. For commercial surface coil protection diodes, a continuous temperature above approximately 125 °C will result in diode destruction, and this new electrothermal model allows MR coil designers the ability to predict temperature effects as part of the full design of the coil.**

***Index Terms* — p-i-n diodes, magnetic resonance imaging, thermal resistance, electrothermal effects, thermal management of electronics.**

I. INTRODUCTION

The typical magnetic resonance imaging (MRI) system contains a large variety of coils. For the radio frequency (RF) portion, these coils include large volume coils, such as birdcage coils, for homogeneous excitation of the MR-specific atomic species, and a variety of receiving coils. A common component in these RF coil assemblies is the PIN diode. The PIN diode is used in a various capacities: on the transmit side, PIN diodes are used to quickly switch the transmitter energy to the transmit coil; and on the receive side, PIN diodes are used for circuit and patient protection and coil detuning. These PIN diodes can be switched actively using DC bias sources controlled by the MRI system controller, or passively, relying on rectified energy to generate the self-bias required for them to change state. Since the PIN diodes are often within the large static magnetic field, the diode and diode packaging must exhibit extremely low magnetic susceptibility, complicating the commercial fabrication of the devices since specialized processes for MR use only must be used. All of these PIN diode features impact the diode's ability to handle the MR transmit power without excessive heating that can ultimately destroy the device.

Modern MRI systems are increasingly using multiple receive coil arrays and systems with 32, 64 or even 128 channels [1,2]. The MR coil arrays can consist of up to 1500 parts that each must work in concert for successful operation of the coil array. For the MR engineer designing such coil arrays, having the ability to perform full time domain electrothermal simulations of the coil and attached electronics would be extremely valuable for studying the interactions of all these components and for their optimization. One such example of optimization for an MR coil array involves simulating circuit response for automated tuning and matching [3]. This paper describes a PIN diode electrothermal model that is suitable for use in SPICE simulators [4] that provides the MR design engineer with an additional tool for use in coil design. The model is described and applied to a single MR receive coil that can be part of a larger coil array. Time domain simulations of both electrical operation and thermal response of a receive coil for a 1.5 Tesla (T) 64 MHz system are shown.

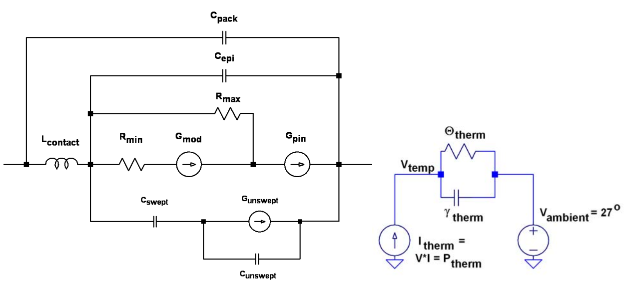
II. PIN DIODE ELECTROTHERMAL MODEL

A full PIN diode time domain model that can be easily implemented in SPICE is used in this work [5-8]. The SPICE model combines the various parasitic capacitances, inductances and resistances with dependent current sources that govern the I-region operation and the two PN junctions (Fig. 1a). The PIN diode RF equivalent circuit as implemented in SPICE is shown in Fig. 1a where Gmod is a dependent source modeling the I-region stored charge effect, Gpin is a dependent source modeling the PN junctions on either end of the I-region, Gunswept is a dependent source modeling the 'unswept' resistance in the I-region, and the other lumped elements describe the various parasitics in the PIN diode.

PIN diode resistance shows a complex variation with temperature due to junction effects as well as I-region mobility and carrier lifetime temperature variations. Thermal effects are implemented using a separate circuit in the SPICE model using a single-pole Foster thermal impedance model with 27 °C as the ambient (Fig. 1b). Thermal resistance Θ_{therm} and the thermal time constant $\tau_{therm} = \gamma_{therm}\Theta_{therm}$ are both inputs to the thermal model. Thermal resistance Θ_{therm} is typically available in manufacturer's data sheets while τ_{therm} requires knowledge of parameters such as the die geometry and thermal bonding to the package [9]. A voltage-equivalent modeling the resulting temperature rise in the device, V_{therm}, is used as one of the controlling elements for the dependent sources Gmod and Gpin in the model and varies their contributions.

III. Application to MRI Surface Receive Coil

Modern MRI receive coils typically used multi-element surface coil arrays. These surface coil arrays improve signal to noise ratio (SNR) since they are in close proximity to the source of the atomic MR signal but this improved SNR only occurs over a small region [1] and so multi-element arrays help keep SNR high while improving the field of view over the imaged region. Decoupling of the individual coil elements in the array is done by offsetting the coils to reduce mutual inductance and by impedance matching the LNAs to a low impedance to minimize coil current [1]. Because these are surface coils tuned to the high power MR transmit signal and are close to the person's skin, they can detune the transmit coil, the receive coils can pick up the high power RF signal and transmit to the patient (in the form of a burn) or to the LNA and cause burnout. For both patient/LNA protection and detuning, PIN diodes are liberally used throughout coil arrays.



(a) (b)

Fig. 1. a) RF equivalent circuit of the PIN diode model showing the model passive and controlled elements (not shown are additional resistances used for simulator convergence); b) Single-pole Foster thermal impedance model with voltage V_{temp} corresponding to the instantaneous device temperature [6].

For patient/LNA protection, PIN diodes operate in an analogous fashion as microwave power limiters; in MR systems, an anti-parallel pair of diodes is frequently used. These diodes bear the full brunt of the received signal from the close proximity MR transmitter and therefore need to be carefully modeled so that the do not suffer extensive temperature rise and device failure. Further, the diode resistance itself is a function of temperature that is approximated by (1) and indicates that the on-state resistance, and therefore limiting potential, can increase or decrease as temperature rises.

$$R(T) = R(T_0)\left(\frac{T}{T_0}\right)^{2.3-mtau} \tag{1}$$

The SPICE model previously described can be used to estimate the degree of limiting afforded by the diode pair and the device temperature rise as a function of received power. The MR pulse duty cycle also plays a role in the level of temperature rise since low duty cycles will allow device cooling during the OFF phase.

An equivalent circuit for a single typical 1.5 T MR receive coil at 64 MHz is shown in Fig. 2. The 4-section coil consists of four 25 nH coil elements and four 185 pF tuning and matching capacitances. Multi-section coils, an example of which is shown in Fig. 2, are widely used in MR systems to minimize radiation and other losses since each coil segment is a small fraction of a wavelength [2]. The LNA signal is obtained across one of the coil capacitors through a transmission line to a PIN diode limiter pair and then another transmission line to the LNA. Specifications for the PIN diodes used in the anti-parallel pair are from a commercially available device for this purpose and an abbreviated list of specifications is shown in Table 1. Time domain simulations of the PIN diode temperature rise in the coil are shown in Fig. 3. Note that almost immediately after the application of the MR transmit pulse, the temperature of the PIN diodes rises rapidly. However, because of the low duty cycle, the diodes have an opportunity to cool to near ambient conditions before the application of the next pulse. In the simulations, power is introduced across one of the 185 pF tuning/matching capacitors (capacitor A in Fig. 2) using a 10 Ω source impedance which matches that of the LNA.

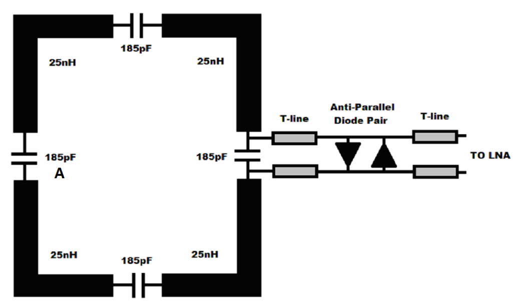


Fig. 2. Equivalent circuit for a 1.5 T 64 MHz receive coil with PIN diode protection circuit. Power to the coil is introduced across capacitor 'A'.

Fig. 4 shows the receive coil input-output power relationship. For low input powers, the output power tracks linearly, indicating that the signal level is small enough for the diode protection pair to be in the off state. Once the input power reaches approximately 26 dBm, the diodes begin to turn on, shunting the line and providing protection. There is approximately 10 dB of protection at 35 dBm input power, with the protection level increasing as the input power increases.

From Fig. 5, the diode temperature remains at the ambient temperature until the RF power at the diode pair rises to approximately 20 dBm (100 mW); the PIN diode temperature then rapidly rises above this power level and exceeds 180 °C as the coil input power approaches 36 dBm (4.0 W). A device temperature of 125 °C occurs at approximately 32 dBm (1.6 W); temperatures at this level and above will often cause failure of the diode pair. The RF pulses shown in Fig. 3 provide peak power of 1.6 W with 0.16 W average power (10% duty cycle for this example).

Table 1. PIN diode parameters

Parameter	**Value**
I-region width (μm)	6
Carrier Lifetime (nS)	12
Carrier lifetime temperature coefficient, *mtau*	2.1
Thermal resistance (^{o}C/W), Θ_{therm}	50
Thermal time constant (μS), τ_{therm}	0.1

This 125 ^{o}C temperature level compares quite favorably with the commercial PIN diode's thermal destruction power level of approximately 2.0 W CW.

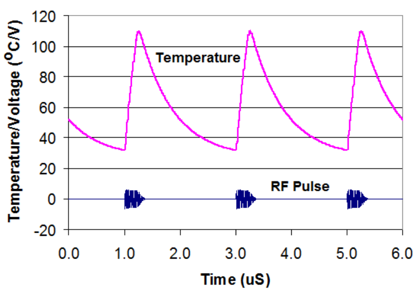


Fig. 3. PIN diode receiver protection circuit heating and cooling with low duty cycle MR transmit pulse.

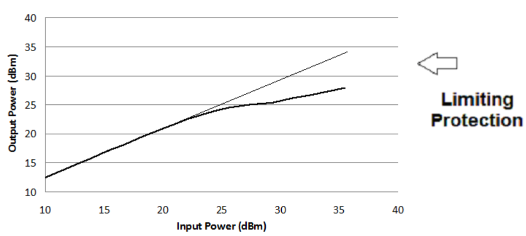


Fig. 4. Input-output power relationship for the surface coil with PIN diode protection.

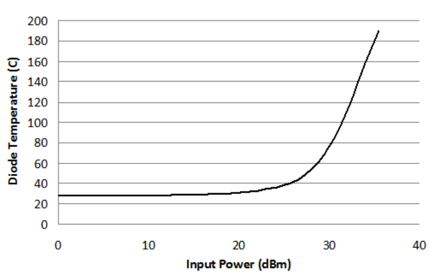


Fig. 5. Temperature rise as a function of output coil power for the PIN diode protection pair.

IV. Conclusion

An electrothermal model suitable for use in SPICE simulations of MR surface coils with their PIN diode protection circuitry has been presented. This model now allows full modeling of both the electrical operation as well as thermal response of high-speed PIN diodes in time domain simulators as part of the overall MR surface coil design. The model offers numerous advantages over earlier diode models that rely on lumped element equivalents for the PIN diode in its on- and off-state in that full electrothermal transient behavior can be modeled. The model results showed good agreement with thermal destruction power levels of the PIN protection diodes. An Excel spreadsheet that calculates the SPICE subcircuit model based on electrical and physical parameters is available at SourceForge.net (Public Domain License):

http://sourceforge.net/projects/pindiodemodel/files/ .

References

1. H. Fujita, 'New Horizons in MR Technology: RF Coil Designs and Trends', *Magnetic Resonance Med. Sci.,* vol. 6 (1), pp. 29-42, 2007.
2. F. D. Doty, G. Entzminger, J. Kulkarni, K. Pamarthy, and J. P. Staab, 'RF Coil Technology for Small-Animal MRI', *NMR Biomed.* vol. 20: pp. 304-325, 2007.
3. S.-M. Sohn, L. DelaBarre, J. T. Vaughan, and A. Gopinath, '8-Channel RF Head Coil of MRI with Automatic Tuning and Matching', *2013 IEEE Intl. Microwave Symp. Digest* , pp. 1-3, June, 2013.
4. LT-SPICE v. 4.08y, Linear Technology Corporation, http://www.linear.com, 2010.
5. R. Caverly, "Time-Domain Electrothermal Circuit-Level Modeling of Microwave and RF PIN Diodes", *2012 IEEE Intl. Microwave Symp. Digest,* June, 2012.
6. R. H. Caverly and S. Khan, 'Electrothermal Modeling of Microwave and RF PIN Diode Switch and Attenuator Circuits', *2013 IEEE Intl. Microwave Symp. Digest* , pp. 1-3, June, 2013.
7. R. Caverly, W. E. Doherty Jr. and R. Watkins, "Time Domain Modeling of MR Linear Balanced Duplexers Switched with Low Magnetic Moment PIN Diodes", *2011 Intl. Symp. Magnetic Resonance in Medicine (ISMRM-11*), May, 2011.
8. R. Caverly, W. E. Doherty Jr. and R. Watkins, "Dynamic Modeling of Low Magnetic Moment PIN Diodes for MR Scanner Applications", *2010 Intl. Symp. Magnetic Resonance in Medicine (ISMRM-10),* April, 2010.
9. 'High Frequency Transistor Primer: Part III - Thermal Properties', Hewlett Packard Co., 1998.