Effect of PIN diode nonlinearity on decoupler circuits in magnetic resonance imaging surface coils

Aasrith Ganti¹,² | Timothy Ortiz¹ | Tracy A. Wynn¹ | Jenshan Lin² | Randy Duensing¹

¹Philips Healthcare, Gainesville, Florida  
²University of Florida, Gainesville, Florida

Correspondence  
Aasrith Ganti, Philips Healthcare,  
Gainesville, FL, and University of Florida,  
Gainesville, FL.  
Email: aasrith.ganti@philips.com

Abstract  
Decoupler circuits are the primary circuits used to maintain safety and image quality in switching magnetic resonance imaging (MRI) surface coils. Decoupler circuits predominantly employ PIN diodes as a switch and their performance is most commonly calculated on the bench at DC and low power RF conditions. The effects of high-power RF on PIN diode decoupler circuits are not usually measured. Experiments at high RF power levels reveal a decrease in the impedance of a typical decoupler as the PIN diode operates in the nonlinear region, effectively increasing the ON-resistance of the PIN diode. The constraints that dictate the start of nonlinearities are studied, and ways to control these nonlinearities are presented. Furthermore, this work is used as a basis to extend and improve upon previous work that established figure of merit (FOM) for PIN diode decouplers. This study is a comprehensive guide for MRI coil designers who face the task of designing decoupler circuits for surface coils and are looking for tools to accurately estimate the dynamic impedance of the circuit over the course of an MRI sequence.

KEYWORDS  
decoupler circuits, high impedance blocking circuits, magnetic resonance imaging, PIN diodes, RF transmit—receiver systems

1 | INTRODUCTION

Magnetic resonance imaging is a high-resolution medical diagnostic modality that exploits the presence of the two quantum spin states of protons inside Hydrogen atoms (1H), which are present throughout the human body. Magnetic resonance (MR) employs three primary magnetic fields. The first is a static field, denoted as \( B_0 \). The second field referred to as “gradient fields” consists of pulsed static fields switched at audio frequencies, resulting in spatially linear magnetic field gradients across the \( B_0 \) field. The third is an RF magnetic field, \( B_1 \), having a frequency that equal to the Larmor frequency of Hydrogen (≈42 MHz per \( B_0/T \)) and the magnitude of \( B_0 \). Clinicians predominantly use MR systems with \( B_0 \) of 1.5 tesla and 3.0 T operating at a \( B_1 \) frequency 64 MHz and 128 MHz. The \( B_0 \) field aligns the protons in the direction of the static magnetic field, and the \( B_1 \) field energizes the aligned protons, rotating their magnetization vectors away from the orientation of \( B_0 \). When the \( B_1 \) field is turned OFF, the energized protons relax to their ground state, emanating a weak RF signal centered around the Larmor frequency. The signal strength is very close to the noise floor −174 dBm/Hz. The sensitivity of the receiving device decreases with the signal strength and is inversely proportional to the distance cubed (1/\( r^3 \)) from the signal source (spin) to the receiving device. The proximity of the RF receive coils to the emanating source is of importance, and therefore surface coils are in general preferred over volume coils. The RF surface coil is a very sensitive near-field antenna, in most cases made of a single loop of copper tuned to resonate at the Larmor frequency. Since the
Transmitter and receiver operate at the same frequency, and in proximity to each other, the sensitive receiver coil components need protection during the high-power transmit phase of the MR pulse sequence. Therefore, to protect both the patient and the coil electronics from the effects of high power transmit $B_1$ which could induce high currents in the coil, every receive coil element employs ‘decouplers’. The current induced in surface coils would otherwise perturb the transmit $B_1$ RF field, distorting the homogenous distribution of RF power in the sample. The decoupler circuit is typically an LC tank circuit resonant at the Larmor frequency, that introduces a high impedance in series with the loop element during the transmit phase of the sequence. This impedance minimizes the induced currents in the receive coil. Thus, the surface coil is rendered nearly invisible to the RF transmit fields. The minimum blocking impedance required to allow less than 5% $B_1$ distortion and prevent image artifacts has been explained by Taracila et al. and is given by (1).

$$\frac{|Z_i|}{S(\text{cm}^2)} \times 5\% = \frac{1}{4} \times f_0[\text{MHz}]$$  \hspace{1cm} (1)

where $Z_i$ is the required decoupling impedance, $S$ is the surface area of the receive coil, and $f_0$ is the frequency of operation. For example, a $10 \times 10 \text{ cm}^2$ loop needs 3.2 kΩ of decoupling impedance while operating at 128 MHz.

The decoupling impedance is directly proportional to the Quality factor ($Q$) of the tank circuit formed by the decoupling capacitor and inductor as shown in Figure 1. Reducing the component losses increases the $Q$ which consequently increases the impedance of the decoupler circuit. Conventional ceramic capacitors used in surface coils have low loss compared to the losses of inductors or switch elements. The performance of the decoupler is dominated by the losses in the inductor and the switch components. Increasing the physical size of the inductor may reduce the resistance losses, but may have drawbacks like visible local $B_1$ distortion due to the field created by the inductor, limiting the design freedom for that component. Therefore, the losses in the switching component primarily dictate the impedance of the decoupler circuit. As this paper will discuss, the ideal switching component should behave as a short in its “ON” state and as an open circuit in its “OFF” state as shown in Figure 2. Decouplers in literature use PIN diodes, FETs, and MEMS devices. The most widely used decoupler switch is the PIN diode.

Decoupler circuits may operate in an active or passive mode. In the active mode of operation, the MR system supplies a control signal to the switching element along with a bias current whereas, in the passive mode of operation, the switching component turns ON via the voltage induced in the loop element by the $B_1$ field and does not require a control signal. For this reason, passive activation is one form of fault tolerance, providing a “failsafe” mechanism should the control signal be interrupted.

The performance of decoupler circuits are most commonly evaluated on the bench in purely DC and low power RF conditions. However, decoupler circuits in the MR system operate under high powers and may affect the performance of the diodes. The effectiveness of PIN diode decouplers under high RF power of MR transmit has not been adequately documented. This paper investigates the influence of RF signals and DC bias on the decoupling impedance of the circuit.
A surface receive coil uses multiple capacitors to resonate the inductance of a single conductive loop or trace in order to reduce E-field losses caused by voltage build-up across the capacitors. Ideally, all the capacitors chosen would have the same reactance. However, to achieve a high blocking impedance, the reactance of the decoupling capacitor \((C_d)\) must be high, implying a lower capacitor value. As shown in Figure 1, when either D1 or D2 is activated (switch closed), it completes a parallel resonant circuit with the decoupling capacitor and inductor \((L_d)\), imposing a high impedance known as the decoupling impedance, along the series path of the loop antenna. An active decoupler is very effective since the galvanically provided control signal renders the diode switch more nearly ideal. Passive decoupler circuits switch states based on the incident RF voltage but provide less decoupling impedance when compared to the active decouplers, as the diode switching behavior is less effective.

Decoupler circuits predominantly use PIN diodes as the switching element because they can withstand high circulating currents generated in the decoupler during the transmit phase of the MR system. These diodes often also have a very low OFF-capacitance and a low series ON-resistance. In an active decoupler, the bias current supplies the charge carriers needed to fill the intrinsic region. Several PIN diode decoupler circuits that work in both the active and passive modes have been proposed. A typical decoupler has two PIN diodes \((D1, D2)\) in an antiparallel configuration as shown in Figure 3A. In another configuration, as illustrated in Figure 3B, a single PIN \((D1)\) diode is used with an antiparallel high power Schottky diode \((D2)\). The antiparallel diode enables the passive mode of operation by functioning as a rectifier diode. The rectifier diode, \(D2\), clamps the voltage during a negative half cycle of the supply and provides a low impedance path for the charge carriers from \(D1\). The diode \(D2\) turns ON when the incident RF voltage is higher than the forward junction voltage of the diode. This phenomenon of alternating diodes turning ON with incident RF power is called self-bias.

The phenomenon of self-bias is observed not only in the passive mode of operation but in the active mode of operation as well. Although a DC bias is supplied during

FIGURE 2  Ideal and realistic working scenarios of the switching element

FIGURE 3  A, Antiparallel PIN diode pair; B, PIN diode with an antiparallel Schottky diode
the active mode of operation to turn the diode (D1) ON and maintain a constant decoupler impedance, a high power RF pulse during the transmit phase of the MR sequence can completely deplete charge carriers from the diode's intrinsic region. This depletion causes charge starvation and a subsequent internal arc, resulting in a damaged diode and decoupler.\textsuperscript{11} The antiparallel diode (D2) protects the PIN diode (D1) from this mode of failure by functioning as a clamp, limiting the reverse voltage across D1. It also provides a path for supplying charge carriers to the PIN diode on the following cycle, maintaining a low resistance, safe “ON” state for the decoupler across both halves of the RF cycle. Equations (2) and (3), first proposed by White,\textsuperscript{12} provide a straightforward and quantitative understanding of the charge accumulated in the intrinsic region by DC bias and the charge displaced by the incident RF current in each half cycle respectively:

\[
\text{DC-Charge} = I_{DC} \times \tau \quad (2)
\]

\[
\text{RF-Charge} = \frac{2 \times I_{peak-RF}}{f_{RF}} \quad (3)
\]

where DC-Charge is the charge deposited by the DC bias current \(I_{DC}\) and RF-Charge is the charge carried by one-half period of the RF current. \(\tau\) is the carrier lifetime of the charge carriers in the intrinsic region, and \(f_{RF}\) is the frequency of the incident RF current. The amplitude of the RF current through the PIN diode is dependent on the impedance of the decoupling capacitor, the \(Q\)-factor of the decoupler, and the size of the surface coil loop. For example, high RF currents per half cycle are possible in large loops. The calculations in Table 1 assume that an RF current of 1 A is incident on the diodes.

The incident RF current always affects the charge in the intrinsic region.\textsuperscript{13} When RF-Charge is greater than DC-Charge, the RF current can displace enough carriers to change the resistance of the intrinsic region. This phenomenon is called charge modulation. If all other parameters remain constant, then diodes are more susceptible to charge modulation at lower frequencies than at higher frequencies (Table 1), because the longer wavelengths at lower frequencies have periods greater than the transit time of the device and therefore move charge out of the diode effectively. Charge modulation results in the formation of three distinct regions of operation as the incident RF power increases.

**TABLE 1** Charge carriers in the intrinsic region

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>Charge\textsubscript{RF} (nC)</th>
<th>Charge\textsubscript{DC} (nC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128 (3 T)</td>
<td>3.9</td>
<td>3</td>
</tr>
<tr>
<td>64 (1.5 T)</td>
<td>7.813</td>
<td>3</td>
</tr>
</tbody>
</table>

This analysis is done assuming a 100 mA bias current applied to PIN diode with \(\tau = 30\) ns.

Figure 4 shows the simulated performance of a diode decoupler with DC bias at various power levels. At low RF power levels, such as might be used for low flip angles, the DC bias turns ON the PIN diode (D1), and the RF power does not significantly influence the charge in the intrinsic region; see Phase I of Figure 4. The diode (D1) behaves as an ideal short while the antiparallel diode (D2) remains OFF and does not influence decoupling. As the incident RF power increases, during Phase II as seen in Figure 4, the negative half period begins to drain the charge in the intrinsic region of the diode (D1) and moves the diode into a nonlinear mode of operation, creating harmonics. In addition, when the amplitude of this incident RF is greater than the junction voltage of the antiparallel diode (D2), that diode turns ON. The diode (D2) clamps the RF voltage to a lower value, reducing the chances of the diode (D1) reaching charge starvation. This phenomenon of self-bias and charge modulation increases the effective ON-resistance of the antiparallel diode pair and consequently decreases the decoupling impedance. At higher power levels (see Phase III in Figure 4), both the applied DC bias and the self-bias keep the diodes turned ON. If one uses this hypothetical decoupler in a 10 × 10 cm loop requiring 3.2 kΩ of blocking impedance, the decoupler will fail to provide the blocking impedance required to have less than 5% \(B_1\) distortion at higher power levels. The equations in ref. 13 further describe the nonlinear functioning of a single PIN diode and are given as (4) and (5).

\[
I_{H2} = -\frac{I_{RF}^2}{I_{DC} \omega \tau} \left( \frac{R_s}{R_s + 2Z_0} \right) \quad (4)
\]

\[
I_{H3} = \frac{\sqrt{2} W}{8} \frac{I_{RF}^3}{I_{DC} \omega \tau^3} \left( \frac{R_s}{R_s + 2Z_0} \right) \quad (5)
\]

\(I_{H2}\) and \(I_{H3}\) represent the second and third harmonic currents produced due to the nonlinearity of a single PIN
diode. However, (4) and (5) are no longer sufficient to describe the harmonic currents when two PIN diodes are connected in an antiparallel configuration. While the complete description of the nature of currents in an antiparallel diode is out of scope for this work, the additional factors affecting the characteristics of harmonic currents are studied. These factors include: incident RF current \((I_{RF})\), supplied DC bias \((I_{DC})\), the series resistance of the intrinsic region \((R_s)\), the resistance of the load \((Z_0)\), angular frequency \((\omega)\), OFF-capacitance \((C_{OFF})\), and the carrier lifetime of the intrinsic region \((\tau)\). Nevertheless, the Equations (4) and (5) describe two significant aspects of this study:

1. In an antiparallel pair, the second harmonic component of current from each of the diodes is out of phase and subtract from each other while the third harmonic components from the diodes add to each other.
2. Device parameters can be changed to improve the nonlinear performance of the diodes.

The harmonic cancellation under high incident RF conditions results in a net loss of total current and a lower decoupling impedance than in the case of low incident RF conditions. Device parameters of the PIN diode such as the width of the intrinsic region \((W)\), carrier lifetime \((\tau)\) as well as nondevice parameters such as the applied DC bias dictate the impedance of the decoupler and the RF power level at which the antiparallel diode turns ON. Varying these parameters can improve the decoupling impedance.

2.1 Increasing DC bias

Increasing the DC bias raises the number of charge carriers in the intrinsic region. The diode \((D1)\) is then less susceptible to charge modulation and nonlinear behavior for an incident RF power, thereby preventing the antiparallel diode \((D2)\) from turning ON. The potential trade-off is the additional DC power needed to supply that additional bias current.

2.2 PIN diode with a higher carrier lifetime \((\tau)\)

A longer carrier lifetime allows a higher charge concentration in the PIN diode’s intrinsic region. Controlling carrier lifetime so that the charge accumulated in the intrinsic region is greater than the charge removed by the incident RF pulse can delay the onset of the nonlinear phase. A consistent higher decoupling impedance is achievable with lower DC bias. One must note that only increasing the carrier lifetime is not trivial since increases in carrier lifetime are most commonly achieved by changing the physical structure of the diode and could imply a wider intrinsic region or a larger diameter of the diode. The increased dimensions result in an increased OFF-capacitance of the diode and could result in a larger signal loss during the receive mode of the MR sequence. The increased loss is caused due to the lower impedance presented by the increased OFF-capacitance of the diode that could create a parasitic path for the MR receive signal.

2.3 Decreasing the width of the intrinsic region of the PIN diode

In contrast, if carrier lifetime is constant, reducing the width of the intrinsic region lowers the ON-resistance even with lower carrier lifetime values. However, decreasing the width also increases the OFF-capacitance of the PIN diode, creating a parasitic capacitive path through the diode, as shown in Figure 2, which can degrade the SNR performance of the receive elements.

2.4 Figure of merit

The figure of merit (FOM) describes the switching performance of the switching element. FOM is dependent on the ON-resistance and the OFF-capacitance of the switch. FOM also provides information on the quality of decoupling achieved by a switching element. This way of quantifying switch performance is commonly known as broadband switch cutoff frequency in the microwave community and has been recently adopted for switches used in decoupler circuits. It was initially proposed in ref. 5 and is given by (6). When the FOM is low, the decoupling performance is more effective.

\[
\text{FOM} = \frac{R_{ON}}{C_{OFF}}
\]

From (6), FOM is simply the product of the ON-resistance and the OFF-capacitance of the switching element.

<table>
<thead>
<tr>
<th>Package</th>
<th>Designator</th>
<th>Type</th>
<th>(\tau) (ns)</th>
<th>(R_{on}) ((100) mA)</th>
<th>(C_{off}) (pF)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antiparallel</td>
<td>Diode 1</td>
<td>PIN</td>
<td>20</td>
<td>0.7</td>
<td>1</td>
<td>Low (\tau)</td>
</tr>
<tr>
<td></td>
<td>Diode 2</td>
<td>PIN</td>
<td>20</td>
<td>0.7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Antiparallel</td>
<td>Diode 1</td>
<td>PIN</td>
<td>60</td>
<td>0.7</td>
<td>1</td>
<td>High (\tau)</td>
</tr>
<tr>
<td></td>
<td>Diode 2</td>
<td>PIN</td>
<td>60</td>
<td>0.7</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Antiparallel</td>
<td>Diode 1</td>
<td>PIN</td>
<td>2000</td>
<td>0.75</td>
<td>1.2</td>
<td>Traditional</td>
</tr>
<tr>
<td></td>
<td>Diode 2</td>
<td>Schottky</td>
<td>N.A</td>
<td>0.098(^a)</td>
<td>144(^a)</td>
<td>PIN</td>
</tr>
</tbody>
</table>

\(^a\)\(R_{on}\) of a Schottky diode is given as \(R_s\) and \(C_{off}\) as \(C_{jo}\) in the datasheet.
In this case, the FOM of a PIN diode can be improved using the methods discussed.

3 | SIMULATION AND EXPERIMENTAL DATA

Simulations and bench top tests were performed on three diode pairs listed in Table 2 to substantiate the claims discussed in the previous sections. The performance with temperature variation is beyond the scope of this experiment; all measurements were carried out at room temperature. Three antiparallel diode pair configurations, low $\tau$—thin I-region diodes, high $\tau$—thin I-region diodes, and a more “traditional” I-region PIN diode with high power Schottky diode in parallel were used for the tests.

3.1 | Simulation—harmonic analysis

Simulations in Keysight ADS performed using Caverly’s PIN diode model mimicked the bench test setup. The decoupler was tuned to the Larmor frequency using the S-Parameter simulation controller, then the impedance of the decoupler and individual diodes were measured using the harmonic balance simulator. Parametric RF power sweeps were performed to measure the impedance of the decoupler while varying carrier lifetimes, bias currents, and diode construction parameters. Figure 5 shows the schematic of the decoupler circuit used for simulation.

The harmonic component data from two diodes, low $\tau$, and high $\tau$ are evaluated using simulations at DC bias of 10 mA, 50 mA, and 100 mA at 22 dBm (LP) and 40 dBm (HP) of input power. As observed in Figure 6A-D, when the bias current supplied to the diodes increases, the total power in the harmonics decreases because, at the higher bias currents, charge carriers fill the intrinsic region, suppress the nonlinear response of the diode D1 and consequently suppress the nonlinear response of diode D2. A null at the sixth harmonic (768 MHz) in Figure 6B can be attributed to harmonic cancellation as explained in the previous section. This null is a characteristic of the chosen simulated conditions and can be observed at other harmonics by varying the simulation conditions described earlier that result in deviation from the behavior predicted in (4) and (5).

3.2 | Simulation—FOM

The simulation schematic from Figure 5 was used to calculate the FOM of PIN diodes across varying power levels. The table below shows the component description, value, and units for the simulation schematic:

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>DC blocking</td>
<td>1000 pF</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td>Decoupling capacitor</td>
<td>18 pF</td>
<td></td>
</tr>
<tr>
<td>R1</td>
<td>Current limiting resistor</td>
<td>15 Ω</td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>RF choke</td>
<td>4.7 μH</td>
<td></td>
</tr>
<tr>
<td>Ld</td>
<td>Decoupling inductor</td>
<td>88.2 nH</td>
<td></td>
</tr>
<tr>
<td>D1,D2</td>
<td>Anti - parallel diodes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zload</td>
<td>Load resistor</td>
<td>50 Ω</td>
<td></td>
</tr>
</tbody>
</table>
the simulation. The variation in the diode pair’s ON-resistance with incident RF power is measured using the harmonic balance simulator. The OFF-capacitance remains unchanged, and its value from the datasheet was used to evaluate FOM.

Note that the FOM is difficult to define for mixed diode pairs such as the PIN and Schottky diode pair and is not considered in this work. This is consistent with the approach taken in previous studies.5 The ON-resistance of the diodes changes continuously with increasing incident RF power. Additionally, one can observe a decrease in the FOM as the diodes approach the nonlinear phase. Figure 7A shows the FOM of low and high τ PIN diodes biased with 100 mA and 30 mA as the RF power varies from 23 dBm to 47 dBm. A plot of the FOM when no DC bias is applied is shown in Figure 7B. Without a DC bias, the antiparallel pair turns ON due to the phenomenon of self-bias, and always operate nonlinearly resulting in a lower FOM when compared to the biased case.

3.3 | Experiment—effect of harmonics on decoupling impedance

The bench test measurement setup consists of a Keysight 5072 A network analyzer with access to the internal couplers and RF Source. This access allowed a 45 dB power amplifier to be connected to the RF source. A circulator and bidirectional coupler were included to maintain a 50 Ω load to the amplifier and to protect Port 1 of the network analyzer from high reflected powers as shown in Figure 8. After calibration, an S21 measurement was performed across the decoupling capacitor (C_d) of the three diode pairs when a bias is applied and power at the resonant frequency, 128 MHz, is swept from 20 dBm to 45 dBm. This setup emulated the RF power induced on the decoupler in an MR system. The R&S HPM4040 with sense lines, configured as a constant current source, imitated the system power supply by providing DC bias to the PIN diodes. The decoupling impedance is measured by performing an S21 measurement and applying the Z–Transmission conversion function on the network
analyzer. The plots in Figure 9A-C illustrate the results of the experiment for low $\tau$, high $\tau$, and thick I-region PIN—Schottky diode pairs at various bias levels respectively. As the DC bias increases, the harmonics generated decrease in both number and magnitude. The RF power at which the diode behavior becomes nonlinear and harmonics begin is the same power level where the series resistance of the diodes increases and decoupler impedance decreases. In the case of thick PIN diodes, at 115 mA the applied RF is incapable of modulating the charge in the intrinsic region, and the decoupling impedance remains constant, implying a constant decoupler impedance.

Increasing the carrier lifetime in the intrinsic region of a device reduces the probability of recombination within the intrinsic region. More charge carriers are thus available for transport, and the conductivity of the diode increases (i.e., works as a better “short”). Figure 9 compares the performance of diodes with different carrier lifetimes. If these decouplers were used on the hypothetical coil, they would not be able to maintain a high decoupling impedance at higher power levels due to the nonlinearity of the diodes. Figure 9A,B are similar diodes but vary in $\tau$. It is seen that the decoupler built with a high-$\tau$ diode (Figure 9B) has a better decoupling impedance and becomes nonlinear at higher power levels. Figure 9D compares data between the three diode pairs as a 60 mA bias is applied. In the linear region, the diodes with low $\tau$ have a lower decoupling impedance than diodes with higher $\tau$. Nonlinearities begin earlier in diodes with lower $\tau$ as compared to the diode with a higher $\tau$. Finally, the impedance at very high-power levels is slightly lower in the low $\tau$ diodes than the high $\tau$ ones. An antiparallel diode pair with a higher $\tau$ remains in the linear mode at higher incident RF powers and maintains a constant high decoupling impedance. It should be noted that the benefits of having a passive failsafe mechanism are lost if a diode with very high-$\tau$ (Figure 9C) is chosen for the design because the ability to turn ON under the influence of RF power and the ability to generate harmonics for self-bias decreases with increasing $\tau$.

### 3.4 | Experiment—OFF-capacitance of the diodes

All the methods described above improve the blocking impedance of the decoupler circuit by reducing the ON-resistance of the diode, but this improvement affects the OFF-characteristics of the diode in a negative way by forming a lossy capacitive path for the signal received by the surface coil (diode turned OFF). Although not prominent, the equivalent circuit of the diode in its OFF state has a very large resistor in parallel to the OFF-capacitance that could contribute to the overall loss of signal received.

![Figure 8](image_url)  
**Figure 8** High power bench test setup
by the surface coil. This parallel resistance is usually very high, on the order of several hundred kΩ or a few MΩ, and is a result of the passivation techniques used while manufacturing the diodes. The presence and effect of this capacitive and resistive path on a resonant loop element were evaluated by measuring the $Q$ factor of a small loop element ($Q_{\text{loop}}$) when a diode was connected. The reduction in $Q_{\text{loop}}$ is related to the loss introduced by the diode. It is essential that the loop element be small since copper losses in large loop elements can overshadow the losses caused by the diode. Decouplers tuned to 128 MHz were placed on a 5 cm × 5 cm loop also tuned to the same frequency. The decouplers were maintained in an off state, and the response of the resonant loop was measured using pickup loops as shown in Figure 10. The diodes have similar construction and manufacturing techniques. The losses between packages were assumed to be constant and therefore neglected for comparative purposes. The change observed in $Q_{\text{loop}}$ is due to the change in capacitance of the intrinsic region and the resistance of the adjacent inductor (Table 3).

The reduction in $Q_{\text{loop}}$ results in a lower signal to noise ratio (SNR) of the reconstructed image. $Q$-factor and the SNR depend on the resistive losses of surface coil ($R_{\text{coil}}$), losses due to the sample being imaged ($R_{\text{sample}}$), and losses that account for diode leakage and soldering ($R_{\text{leakage}}$). Equation (7) relates the SNR to the losses in the loop.\textsuperscript{15} A PIN diode with a larger intrinsic region can therefore cause a higher loss and reduce the SNR of the reconstructed image.

### TABLE 3 Change in $Q$ due to diode losses

<table>
<thead>
<tr>
<th>Device</th>
<th>Unloaded $Q_{\text{loop}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No diode</td>
<td>188</td>
</tr>
<tr>
<td>Low $\tau$</td>
<td>156.2</td>
</tr>
<tr>
<td>High $\tau$</td>
<td>145.3</td>
</tr>
<tr>
<td>Thick PIN with Schottky</td>
<td>131.2</td>
</tr>
</tbody>
</table>

FIGURE 9  Measured Impedance of decouplers with (A) low $\tau$ (B) high $\tau$ diodes and (C) thick PIN, Schottky with varying DC bias (D) Comparison of the three diodes pairs with a 60 mA bias current

FIGURE 10  Test setup for measuring $C_{\text{off}}$
The results presented verify that the decoupling impedance is not constant and varies according to the device parameters and the bias applied. The observation of harmonics implies nonlinear operation within the diodes, and charge modulation in the intrinsic region is due to incident RF. A more important observation is that the FOM given by (6) varies for the entire region of operation. This critical observation has not been documented before and is of great importance for coil designers since the decoupler circuit has a direct and significant impact on image quality and for maintaining the safety of the patient. The rate at which FOM changes with incident RF power should also be used as a parameter to compare different diode pairs.

The high \(\tau\) diode in Table 5 exhibits nonlinearity at a higher power level, and it will have a better FOM than the diode with low \(\tau\).

When choosing PIN diodes for decouplers, their performance across different power levels should be evaluated. As compared to switch elements presented in literature, PIN diodes have the best FOM in the conditions discussed above. As seen in Table 5, though the FETs have an advantage over PIN diodes with low and constant ON-resistance, they have an inherent problem. They may not withstand high circulating currents produced in the decoupler circuit. In the case of large FETs that can withstand high circulating currents, the OFF-capacitance is too high, thereby affecting the FOM. Twieg et al.\(^5\) used a FET with a large area, which consequently had a large OFF-capacitance. Lu et al.\(^6\) used a depletion mode FET in their studies and reported failure on a device with the lowest capacitance when the circulating current was higher than the drain current at zero bias (\(I_{DSS}\)).

This study focused on the 3T decoupler circuit operating at 128 MHz. A similar analysis can be performed for the 1.5T decoupler circuit operating at 64 MHz. When similar diodes are used, charge modulation is comparatively more predominant in the diodes operating at lower frequencies, and as a result, enter the nonlinear phase (Phase II and Phase III as seen in Figure 4) at a lower power level. Due to this higher nonlinearity, the diodes are more resistive while operating at 64 MHz than while operating at 128 MHz. Also when a low \(\tau\) diode is used, the operating frequency (64 MHz) is less than \(\frac{10}{2\pi\tau}\) and results in increased junction effects, further reducing the decoupler’s performance. Therefore, by choosing diodes with larger carrier lifetimes, the onset of nonlinearity can be delayed. Also, at a lower frequency of operation, the \(C_{OFF}\) has a reduced impact on the receive performance of the loop element since it behaves like a smaller parasitic path. Therefore, diodes with higher \(\tau\) and consequently higher \(C_{OFF}\) can be used at lower frequencies for improved decoupling performance.

## DISCUSSION

### TABLE 5 FOM of anti-parallel diodes

<table>
<thead>
<tr>
<th>Device</th>
<th>30/100 mA @ 23 dBm</th>
<th>30/100 mA @ start of nonlinear mode</th>
<th>30/100 mA @ 47 dBm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low (\tau)</td>
<td>1.56/0.87</td>
<td>3.73/1.77 (26.7 dBm/36.7 dBm)</td>
<td>1.12/1.14</td>
</tr>
<tr>
<td>High (\tau)</td>
<td>0.5/0.3</td>
<td>1.81/0.77 (33 dBm/40 dBm)</td>
<td>0.6/1.1</td>
</tr>
</tbody>
</table>

\[
\text{SNR} = \sqrt{ \frac{R_{\text{sample}}}{R_{\text{sample}} + R_{\text{coil}} + R_{\text{leakage}}} }
\]

\[
(7)
\]

## CONCLUSION

In this work, PIN diode decoupler circuits were studied in detail on the bench using a high-power network analyzer and in simulations, using Keysight ADS. Simulation and bench test data agree with the concept of charge modulation affecting the decoupling impedance of the circuit. A higher and constant decoupling impedance can be achieved by choosing fast switching PIN diodes with longer carrier lifetimes, narrower intrinsic regions, or by supplying a higher DC bias. A diode with a longer carrier lifetime can sustain a high decoupling impedance using a lower DC bias current. The paper also discusses the various phases or stages a PIN diode decoupler goes through while under the influence of the high-power MR transmit sequence. This knowledge gives the coil designer information for selecting PIN diode decoupler circuits that maintain a constant high impedance through the MR transmit sequence. The assessment of PIN diodes’ FOM revealed the importance of the nonlinear behavior of the diode when comparing it to alternative decoupling designs in literature such as FETs. The FET’s low power dissipation is an advantage over the PIN diodes, but proper design considerations can reduce the DC bias requirements of PIN diodes, and therefore power dissipation as well.


ORCID

Aasrith Ganti http://orcid.org/0000-0003-3182-6326

REFERENCES


AUTHOR BIOGRAPHIES

Aasrith Ganti is pursuing his Ph.D. in electrical engineering from the University of Florida, Gainesville, FL, USA. He graduated with his B.S in Electronics and Communication Engineering from J.N.T University, Hyderabad in 2008 and Masters in Electrical Engineering from the University of Florida in 2012. He has been working as an Electrical Engineer for Philips Healthcare in the Research and Development group, Gainesville, FL. His research interests include Wireless Power, RF circuits, and systems as applied to medical devices particularly geared toward Magnetic Resonance Imaging.

Timothy Ortiz received his B.S. and M.S. from the University of Florida, where his focus was on RF IC design. He joined Philips in April 2011 and is currently a Research Technologist. Current research topics include wireless medical transceiver and energy harvesting technology design. Before joining Philips, he worked for Motorola research and development on multiple wireless standard and technologies including BT, GPS, GSM, WCDMA, LTE, and 802.11x.

Tracy A. Wynn received B.S. degrees in Electrical Engineering and Applied Mathematics in 1999 and an M.S. degree in Electrical Engineering in 2002 from Florida State University in Tallahassee, Florida. In 2010 he received his M.B.A. from the University of Florida in Gainesville, Florida. He joined MRI Devices in 2002 (later Philips/Invivo) in Gainesville, Florida as an RF engineer, designing MRI coils. He has worked on numerous research and commercial MRI coil products during his tenure, in various design and administrative capacities. He now serves as the Lead RF Architect for Patient Interface at Philips/Invivo.

Jenshan Lin received the Ph.D. degree in electrical engineering from the University of California, Los Angeles, CA, USA, in 1994. He was with Lucent Bell Labs, Murray Hill, NJ, USA, from 1994 to 2001, and Agere Systems, Holmdel, NJ, USA, a spin-off company of Lucent Bell Labs, from 2001 to 2003. In 2003, he joined the
University of Florida, Gainesville, FL, USA, where he is currently a Professor. Since October 2016, he has been on assignment to work for the U.S. National Science Foundation as a Program Director in Communications, Circuits, and Sensing Systems (CCSS) Program. He has authored or coauthored over 260 technical publications in refereed journals and conference proceedings. He holds 15 U.S. patents. His current research interests include sensors and biomedical applications of microwave and millimeter-wave technologies, wireless power transfer, and wireless communication systems. Dr. Lin was a recipient of the 1994 UCLA Outstanding Ph.D. Award, the 1997 Eta Kappa Nu Outstanding Young Electrical Engineer Honorable Mention Award, the 2007 IEEE Microwave Theory and Techniques Society (MTT-S) N. Walter Cox Award, the 2015 IEEE Wireless Power Transfer Conference Best Paper Award, the 2016 Distinguished Alumnus Award from National Chiao Tung University, Hsinchu, Taiwan, and the 2016 IEEE RFIC Symposium Tina Quach Outstanding Service Award. He was the General Chair of the 2008 RFIC Symposium, the Technical Program Chair of the 2009 Radio and Wireless Symposium, and the General Co-Chair of the 2012 Asia–Pacific Microwave Conference. He served as the Editor-in-Chief of the IEEE Transactions on Microwave Theory and Techniques in 2014-2016.

Randy Duensing received his BS and ME in Electrical Engineering and Ph.D. in Physics from the University of Florida, Gainesville, FL. He cofounded Applied Resonance Technology in 1991 and was the President until a merger in 1998. For the new entity, MRI Devices, Dr. Duensing served as the Manager of Research and Pre-Development and was a member of the Board of Directors. After an acquisition by Intermagnetics, and subsequently this company by Philips, he has served as Chief Scientist and Director of the Technology Architecture Group for Invivo Philips, Gainesville, FL. Dr. Duensing is currently the Department Head for Tomographic Imaging Research in Hamburg, Germany for Philips GmbH, Innovative Technologies. He holds 14 US patents and has published extensively in the areas of MR hardware and reconstruction methods.

How to cite this article: Ganti A, Ortiz T, Wynn TA, Lin J, Duensing R. Effect of PIN diode nonlinearity on decoupler circuits in magnetic resonance imaging surface coils. Concepts Magn Reson Part B. 2018;48B:e21398. https://doi.org/10.1002/cmr.b.21398