Understanding and Modeling the Non-Monotonic Attenuation Behavior of PIN Limiter Diodes

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Abstract

A commonly observed and unexplained behavior in limiter and switch circuits using PIN diodes is that attenuation may unexpectedly remain constant and even decrease with increasing input power or dc forward bias. This paper will demonstrate that this anomalous, non-monotonic behavior is attributed to an interaction of the forward biased PIN diode capacitive reactance with any parasitic inductance in series with the junction. A model based on these principles is presented and verified with experimental microwave performance data that should prove useful to the designer.

Introduction

A common anomalous behavior observed in limiter and switch circuits that use PIN diodes is that attenuation often remains constant or even decreases as input power or dc bias is increased. According to the conventional current controlled resistance model of the PIN diode in a limiter or shunt connected switch, the attenuation should always increase as input power or forward dc bias increases. The cause of this anomalous behavior, sometimes incorrectly attributed to losses in the circuit, has never been completely understood. This anomalous behavior is actually caused by a natural interaction and possible resonance between the forward biased PIN diode and any external inductance (bond wire or package inductance) in series with the junction.

This paper presents a model of the forward biased PIN diode that shows that in combination with a series inductance the two elements may exhibit a resonance that is a function of the diode's impedance governing parameters (I-region thickness, carrier lifetime, frequency and dc bias current) and the value of the series inductance. It will also be shown that the PIN diode capacitance reactance is due to conductivity modulation in the I-region and is independent of junction capacitance. This characteristic is not described by the traditional model of the PIN diode as a current controlled resistance.

This more accurate model will allow design engineers to better predict the non-monotonic attenuation versus current or input power for a switch or limiter under the working conditions of the circuit. The model is validated with experimental data on a shunt connected PIN diode demonstrating the anomalous attenuation behavior.

Analysis

When a PIN diode is forward biased, its equivalent circuit has been generally described as a current controlled resistor in parallel with its junction capacitance. In actuality there is also a current controlled reactance that is in series with this resistance; both are the result of conductivity modulation and are frequency dependent.

Figure 1 shows a circuit model for the PIN diode and external series inductance. The parameters R_{PIN} and X_{PIN} shown in the figure are the PIN diode resistance and reactance caused by a combination of junction reactance and reactance due to conductivity modulation in the forward biased I-region. The reactance in PIN diodes has been shown to be a function of frequency, I-region width (W) and carrier lifetime (τ) [1,2]. The capacitance C_J is the I-region capacitance due to the PIN diode geometry and is usually small and may be neglected. L_{BOND} is the series inductance such as caused by a bond wire or package parasitic.

Figure 2 illustrates a normalized curve of X_{PIN} (at 1mA dc forward bias) versus the frequency-carrier lifetime product with the I-region width to I-region

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diffusion length (W/L) plotted as a parameter. The graph indicates that, depending on the I-region thickness W and the I-region carrier lifetime (via the recombination length $L=\sqrt{D_a \tau}$), the reactance of the PIN diode may be capacitive or inductive as a function of frequency. It should be noted that this inductive reactance (or capacitive reactance) is not the result of bond wires (or junction capacitance), but rather is a naturally occurring phenomenon caused by conductivity modulation in forward biased PIN diodes [1,2]. Figure 3 shows the effect of dc bias current on the PIN diode reactive component. The figure results are based on a PIN diode with a W/L of 0.3, a value common to PIN limiter diodes. The results show that the reactive component is capacitive and decreases with increasing dc bias current, regardless of the frequency of operation.

When the reactance is inductive, typical for a switching PIN diode with a W/L ratio greater than unity, its effect may not be noticeable in many designs. However, in limiter or switch circuits the PIN diodes used are designed with W/L values less than unity resulting in a PIN diode reactance that is capacitive. It is primarily this capacitive reactance component of the PIN diode that interacts and may even resonate with any external series inductance and cause the impedance of the PIN diode shunt element to decrease monotonically with increasing dc bias or input power. This will subsequently result in an attenuation versus current characteristic that is also non-monotonic.

Figure 4 shows the impedance magnitude |Z|, resistance (R) and reactance (X) measured at 1 GHz for a 1.7 micron I-region width PIN diode with a 3.5 ns carrier lifetime (W/L=0.65) and a 1.5 nH bond wire inductance. It indicates a localized minimum in the magnitude of the PIN impedance (diode plus bond wire), which occurs at resonance but before the diode resistance reaches its minimum value. For a shunt connected switch, this will translate into a circuit attenuation that will decrease as the forward bias current increases above approximately 1.0 mA. This minimum is the resonance point of the PIN diode capacitive reactive component with the bond wire inductance.

An analysis of the attenuation equation for a simple shunt connected impedance element consisting of a resistance R in series with an inductive reactance ωL also shows a non-monotonic characteristic:

$$\text{Attenuation} = 10\log[1+\frac{RZ_0+\frac{Z_0^2}{4}}{R^2+(\omega L)^2}]\ \text{dB} \qquad (1)$$

An unexpected attribute of this expression is that maximum attenuation does not occur at zero resistance; instead it occurs at the value:

$$R=\sqrt{\frac{Z_0^2}{4}+(\omega L)^2}-\frac{Z_0}{4}\quad \Omega \qquad (2)$$

The effect of this is shown in Figure 5 and again in Figure 7. It indicates that at 1 GHz for a 1.5 nH inductor (typical for a SOT packaged PIN diode) and zero ohms resistance the isolation is 9.05 dB; however, at 3.16 ohms the isolation increases to 9.51 dB. It also shows that the isolation at 7.1 ohms is the same as the isolation at zero ohms. Thus, isolation does not degrade from its zero ohm resistance value even though the resistance has increased to 7.1 ohms. Therefore, the isolation for a conventional forward biased PIN switching diode operating as a current controlled resistor will be non-monotonic as resistance approaches zero ohms in the presence of series inductance. In the case shown the difference in isolation from its maximum to the zero ohm point is 0.46 dB.

For the limiter PIN diode described here it will be shown that its semiconductor junction and I-region contribute an additional series reactance. The resulting interaction of this series reactance with an external inductance may lead to a resonance and cause a non-monotonic isolation effect that is more significant than 0.46 dB.

Experimental Results

Switch measurements were taken on a 1.7 micron, 3.5 nanosecond PIN diode designed as a limiter diode. Figure 6 shows the results of these measurements taken at 1.0 GHz and compared with the PIN diode model and impedance measurement described earlier. Note the non-monotonic attenuation behavior and the general agreement between the theory and the measured data. This demonstrates the expected resonance between the PIN diode reactance and the bond wire inductance. The differences in the measured data and the model are most likely due to uncertainties in the PIN diode's exact electrical and physical parameters, primarily W and τ.

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Figure 7 shows measurements of shunt attenuation versus current over the range of 500 MHz to 2.0 GHz. The results show that the peak isolation decreases with increasing frequency due to the changing resonance point of the X_{PIN} and L_{BOND} combination. Note that the difference between the attenuation peak and the high current attenuation increases with frequency, ranging from 2.25 dB at 500 MHz to more than 5.0 dB at 2.0 GHz. These peak differences are significantly larger than the simple R-ωL model's 0.46 dB difference discussed earlier, indicating the dramatic role of X_{PIN} in governing limiter attenuation.

Conclusions

This paper explains and presents a model of the anomalous, non-monotonic attenuation behavior often observed in PIN switch and limiter diode applications. It shows that the root cause is a capacitive reactance resulting from conductivity modulation, although a smaller scale behavior occurs strictly due to the R-ωL characteristic. Its model, which is a refined and more accurate representation of the PIN diode than the conventional resistance versus current model, will allow better prediction of performance in microwave and RF limiter and switch circuits.

Acknowledgment

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References

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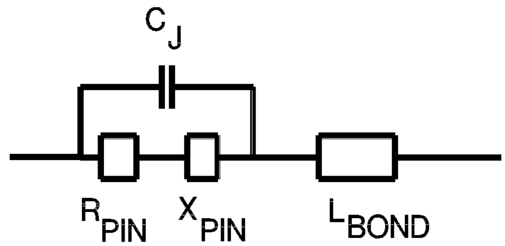

Figure 1. Model of the PIN diode with bond wire inductance included.

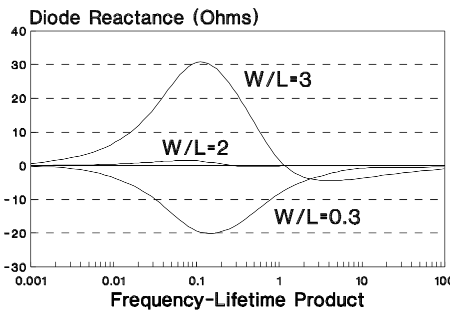

Figure 2. Graph of simulated PIN diode reactance (at 1 mA) plotted as a function of the frequency-carrier lifetime product (fτ).

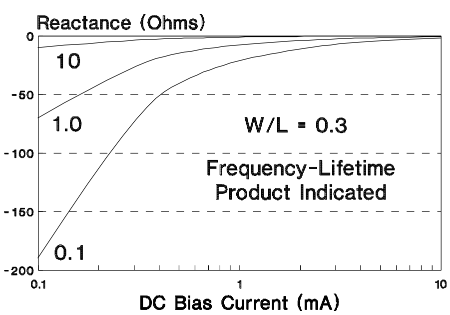

Figure 3. Graph of simulated PIN diode reactance plotted as a function of the dc bias current for three frequency-carrier lifetime products.

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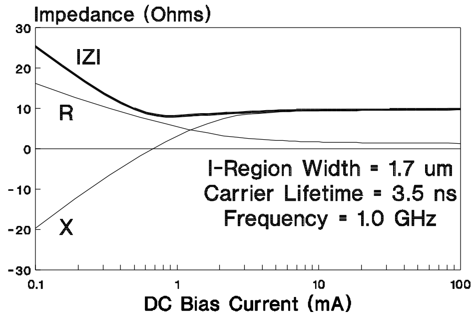
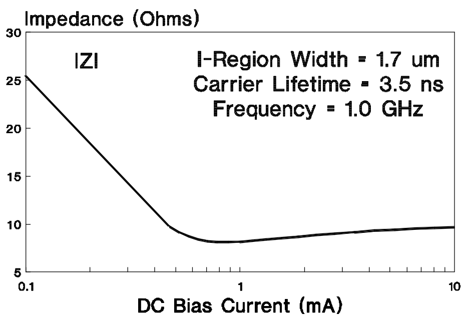


(A)



(B)

Figure 4. A). Graph of the impedance magnitude (|Z|), resistance (R) and reactance (X) of the PIN diode and series inductor (1.5 nH) versus DC bias current, indicating a localized minimum in the impedance magnitude.

B). An expanded graph of |Z| shows this localized minimum in more detail.

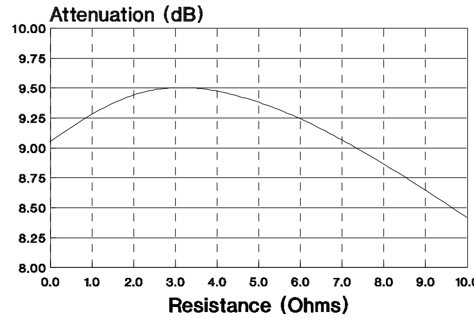


Figure 5. Graph of attenuation for a shunt connected resistance in series with a 1.5 nH inductance at 1.0 GHz.

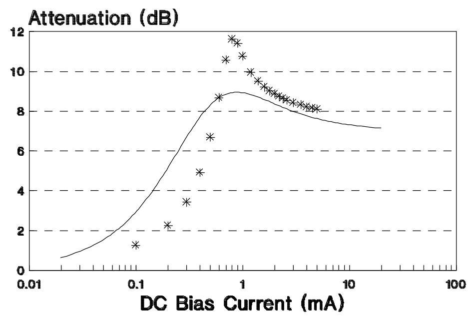


Figure 6. Graph of the PIN diode limiter model (solid line) compared with measured data on a 1.7 micron, 3.5 nanonsecond PIN diode at 1.0 GHz with a 1.5 nH series inductance.

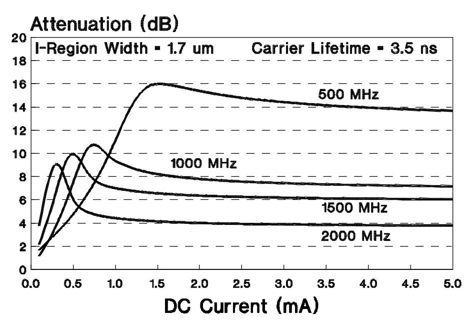


Figure 7. Plot of measured attenuation data as a function of dc bias current with frequency as a parameter.

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