A Low Cost, Compact, Pi-Configured PIN Diode VCA

A careful design approach results in an attenuator that meets cost and performance criteria

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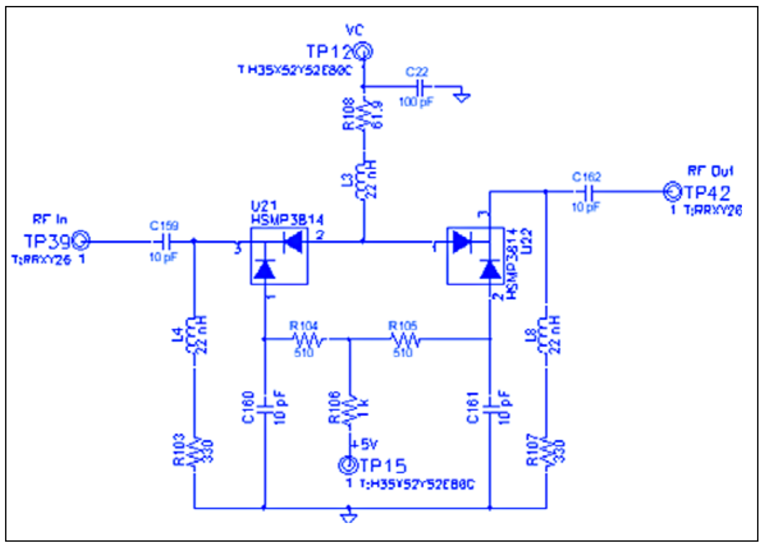
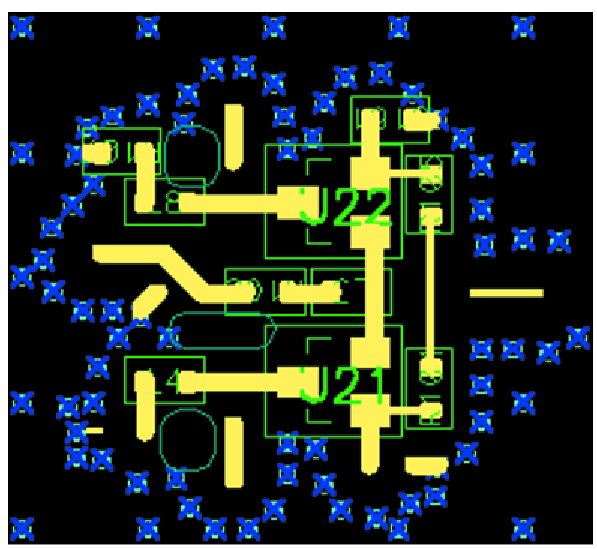
A voltage controlled attenuator (VCA) is an important building block in modern communication transceivers. In a receiver chain, a VCA is typically used to automatically adjust incoming RF signal levels to prevent overdrive LNA, which prevents receiver saturation and desensitization. In transmitter chains, the VCA is used to control output power levels. Especially in today's CDMA systems, a strictly power control led scheme can prevent near-far problems, which may increase the overall capacity in each cell.



▲ **Figure 1. Schematic of the PIN diode-based VCA.**

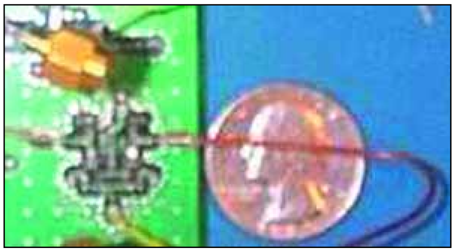
There are several ways to implement a VCA. One commonly used approach is to adjust bias current in the transistor. The problem with this approach is that the P_{1dB} of the transistor drops considerably as bias current drops. Such intermodulation performance becomes worse as the attenuation increases. The bias current has to comprise a large range for a high attenuation range. This can make matching very difficicult unless resistive matching is used. On the other hand, the problems associated with a transistor based VCA can be alleviated considerably if a PIN diode based VCA approach is used.

This article discusses a pi-configured PIN diode-based VCA. The PIN diode-based VCA is a well-known design approach dating back to the vacuum tube era. The schematic, layout and picture of the 2.45 GHz design are shown in Figures 1, 2 and 3, respectively.



▲ **Figure 2. Layout of the PIN diode based VCA.**

The design consists of four PIN diodes. The



▲ **Figure 3. A PIN diode-based VCA.**

discrete design, the plastic-packaging and the use of PIN diodes make this kind of VCA inexpensive to build. The size of the circuit is smaller than a U.S. quarter. Since attenuated power is dissipated in all four diodes, power handling capability is better than in its transistor based counterpart. Good input and output matching can be achieved with careful design. With good matching performance, the VCA behaves as an absorptive termination where no incoming signal is reflected back to the source. A reflected signal is highly undesirable in most applications, and particularly in high power applications.

Before introducing the pi-configured PIN VCA design, we will briefly discuss fixed attenuation pads and PIN diodes. This will demonstrate the transition from a fixed attenuation pad to a PIN diode-based VCA.

T- or pi-configured resistive networks are the most commonly used fixed attenuation value pads. In this article, a pi-configured pad is discussed. Attenuation pads typically require a good input/output port match to 50 ohms and precise attenuation. The standard design equation is contained in a MathCad file, as shown in List 1. *R_s* and *R_l* are the termination values. In this case, 50 ohms is used for both ports. The desired attenuation value is given in dB. The output is the value for the three pi-configured resistors. *Rc* is the middle series resistor, while *Rb* and *Ra* are the shunt resistors on the side. A few experiments will give more insight into the design. Attenuation pads at attenuation levels of 2, 10, 20 and 30 dB are calculated and tabulated; the results are shown in Table 1.

With the resistor values detailed in Table 1, precise attenuation and perfect port matching can be achieved. Table 1 reveals a trend: as attenuation increases, the series resistor value increases, and the shunt resistor value decreases. Intuitively, the trend makes perfect sense. If 0 dB attenuation is needed, the series resistor will be 0 ohms while the shunt resistor value will be infinite. On the other extreme, infinite attenuation requires the series resistor value to be infinite and the shunt resistor to be 0 ohms.

The variable resistor is achieved using the PIN diode, which is basically a silicon semiconductor diode consisting of intrinsic materials of finite area and thickness. The intrinsic material is enclosed by highly doped π and n type materials. Interestingly, the PIN diode will theoretically behave as a pure resistor at a RF frequency with the proper bias current. The PIN diode resistor

$$R\_s := 50, \quad R\_l := 50$$

$$G\_s := \frac{1}{R\_s}, \quad G\_s = 0.02,$$

$$G\_l := \frac{1}{R\_l}, \quad G\_l = 0.02$$

$$Att\_dB := 6, \quad Att\_N(Att\_dB) := \frac{Att\_dB}{8.686},$$

$$Att\_N(Att\_dB) = 0.691$$

$$Gc(Att\_N) := \frac{\sqrt{G\_s \times G\_l}}{\sinh[\mathrm{Att\_N(Att\_dB)}]}$$

$$Gc(Att\_N) = 0.027$$

$$Ga(Att\_N) := \frac{G\_s}{\tanh(Att\_N(Att\_dB))} - Gc(Att\_N)$$

$$Ga(Att\_N) = 6.645 \times 10^{-3}$$

$$Gb(Att\_N) := \frac{G\_l}{\tanh(Att\_N(Att\_dB))} - Gc(Att\_N)$$

$$Gb(Att\_N) = 6.645 \times 10^{-3}$$

$$Rc(Gc) := \frac{1}{Gc(Att\_N)}, \quad Rc(Gc) = 37.351$$

$$Rb(Gc) := \frac{1}{Gb(Att\_N)}, \quad Rb(Gc) = 150.478$$

$$Ra(Gc) := \frac{1}{Ga(Att\_N)}, \quad Ra(Gc) = 150.478$$

▲ **List 1. The standard design equation in a MathCad file.**

value will vary with bias current. This property makes the PIN diode an ideal candidate for VCA design.

The VCA design should be apparent now that the fixed attenuation pad and PIN diode have been explained. The PIN diode-based VCA is essentially a fixed resistor attenuation network in which the fixed value resistors are replaced with variable resistance PIN diodes. In theory, only three PIN diodes are needed. However, the resulting bias network is cumbersome and complicated, so one more PIN diode is added in the series path to creat a more balanced circuit. Balanced, configured PIN diode circuits can cancel the even order distortion product. The bias network is also easier to

Att (dB)	2	10	20	30
Rc (Ω)	11.63	71.15	247.5	789.7
Ra (Ω)	436.2	96.25	61.11	53.27
Rb (Ω)	436.2	96.25	61.11	53.27

▲ **Table 1. Resistor values of the fixed attenuation pad at attenuation levels of 2, 10, 20 and 30 dB.**

Part	Vendors	Number
PIN	Agilent	HSMP3814 x 2
Cap	AVX	10 pF x 4
Cap	AVX	100 pF x 1
Ind	Coilcraft	22 nH x 3
Res	KOA	61.9 x 1
Res	KOA	510 x 2
Res	KOA	1k x 1
Res	KOA	330 x 2

▲ **Table 2. Materials used for the design of the PIN diode-based VCA.**

design.

In designing the bias network, keep in mind what the article has covered so far. Also note that R108, R103 and R107 are used to bias the series PIN diode; R103, R107, R104, R105 and R106 are used to bias the shunt PIN diode; C159 and C162 are DC blocks; and L3, L4 and L8 are RF chokes. With high bias current, PIN diodes will give low resistance, and vice versa. A bias network can be achieved by trial and error on the lab bench. In this particular design, R108, R103, R107, R104, R105 and R106 are 61.9, 330, 330, 510, 510 and 1k ohms, respectively. This particular set of resistors maintains the proper series/shunt resistor ratio very well; therefore, good input and output matching are achieved. The RF choke is implemented with a 22 nH chip inductor that has a high enough impedance to block the RF energy. A DC block capacitor of 10 pF is a low enough impedance for passing RF energy at 2.45 GHz. In this particular design, low insertion loss (less than 2 dB) is highly desirable. The RFC inductor and DC block are carefully chosen and optimized to minimize the insertion loss at 2.45 GHz. The necessary materials are listed in Table 2.

The pi-configured VCA is designed and built for 2.4 to 2.5 GHz unlicensed ISM band. The circuit is built on a FR-4 low cost substrate. With I_{bias} = 26.5 mA, the lowest insertion loss is –2.5 dB. It includes a cable and connector loss of about 0.4 to 0.5 dB. With I_{bias} = 0 mA, the highest insertion loss is –37 dB. Checking the return loss (RL) at both the input and output ports reveals whether the VCA is absorptive instead of reflective. The RL is excellent below –20 dB in most cases for this design. The worst case RL is still –14 dB, which is good enough for most applications.

The test result of the attenuations of –2.5, –10, –20, –30 and –37 dB are shown in the Appendix. For each attenuation value, insertion loss (IL) and RL at the input and output ports are presented.

Generally, the pi-configured VCA has a very wide bandwidth. In theory, the bandwidth is from DC to daylight if a perfectly open and short state can be accomplished from DC to daylight. Early test results show that there is essentially no difference in performance from 2 to 3 GHz. A quick look shows this design can be pushed up to 4 GHz with a 30 dB dynamic range and insertion loss of less than 2.5 dB. In the practical VCA design, there is a less dynamic control range at higher frequencies than there is at lower frequencies. In this particular design, the wide bandwidth is traded for low insertion loss. The frequency optimization is reflected by the RF choke and DC block selection. One of the limitations is the variable PIN diode resistor value. A good PIN diode can achieve a range from 2 ohms to about 500 ohms — still far from 0 to infinity. Another limitation concerns the PIN diode package. The diode package's parasitic inductance will limit the VCA's high frequency performance and, although some clever parasitic inductance cancellation scheme can be used, it will increase cost and design complexity.

With improvement of the PIN diode process, smaller higher-quality packaging, more dynamic range and higher operating frequency, a pi-configured VCA can be achieved in the near future. This design performs well and is also cheap to manufacture; with high volume production quantity, the total cost will be less than $1. An even cheaper circuit can be built. The RFC chip inductor can be replaced with high impedance microstrip line if there is sufficient space. The two shunt RF choke inductors can also be taken out completely; this, however, will increase the minimum insertion loss, since some of RF energy will leak through two shunt bias branches.

A PIN diode is a standard product that most major semiconductor manufacturers will produce. In this design, Agilent's HSMP3814 PIN diode is used. Other PIN diodes, such as Infineon's BAR63 and BAR81 and Alpha Industries' SMP1307-011, are also worth trying. The HSMP3814 PIN diode features two diodes in one package, which reduces component count as well as board space. This is one reason it is used for this design. The other PIN diode should perform similarly. The cost of the PIN diode most likely will be the most important factor when choosing a diode. ■

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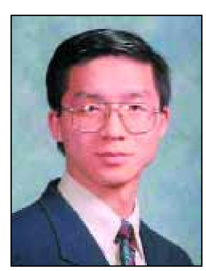
Author information



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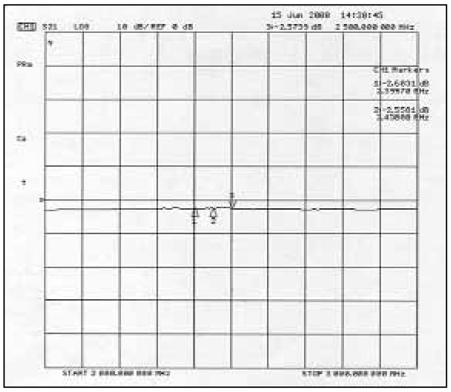
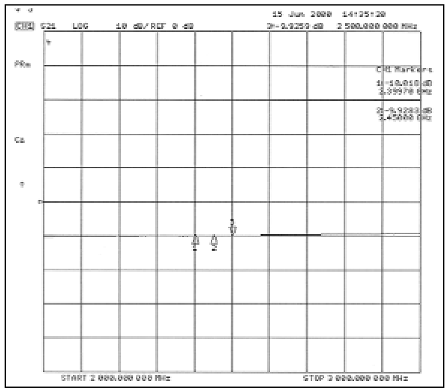
Appendix

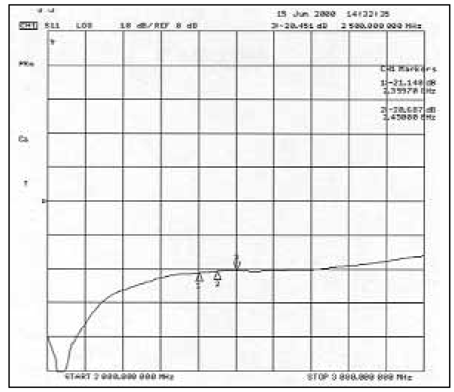
Attenuation values for the PIN diode VCA design.



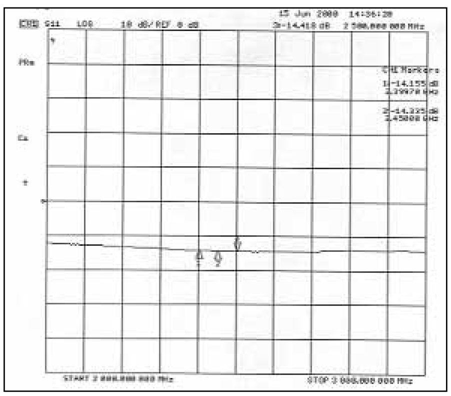
▲ IL = 2.5 dB.



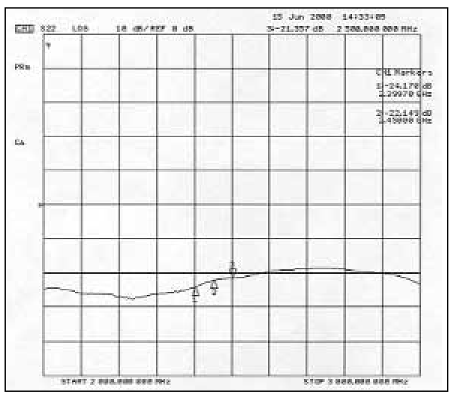
▲ IL = 10 dB.



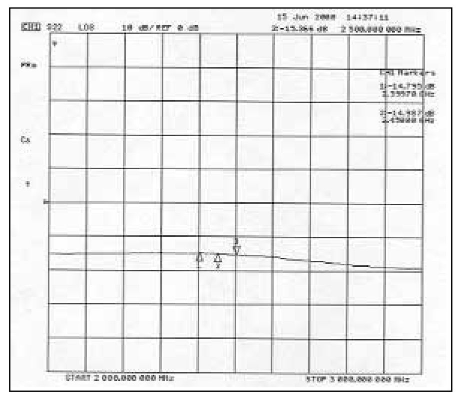
▲ Input matching with IL = 2.5 dB.



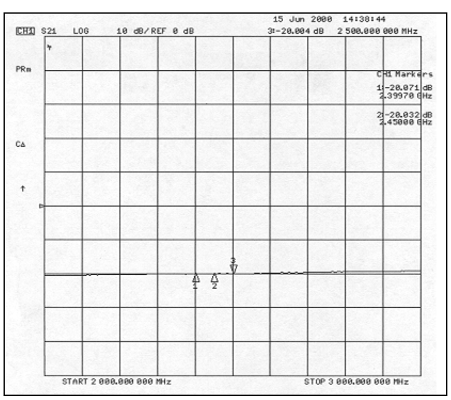
▲ Input matching with IL = 10 dB.



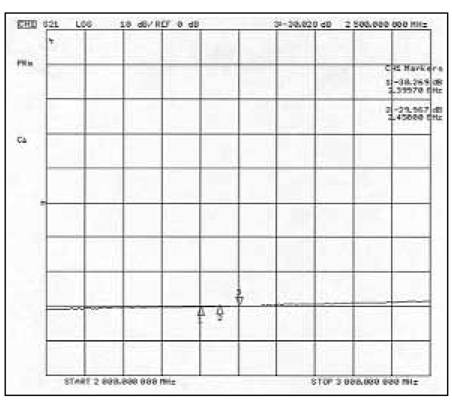
▲ Output matching with IL = 2.5 dB.



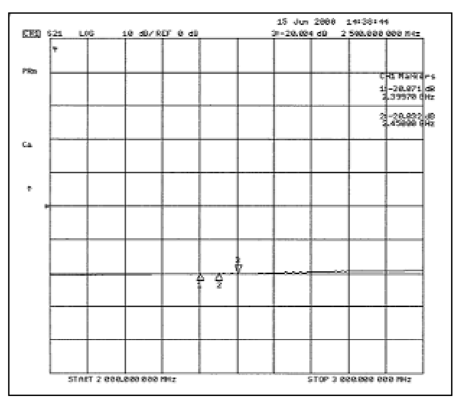
▲ Output matching with IL = 10 dB.



▲ IL = 20 dB.



▲ IL = 30 dB.



▲ Input matching with IL = 20 dB.

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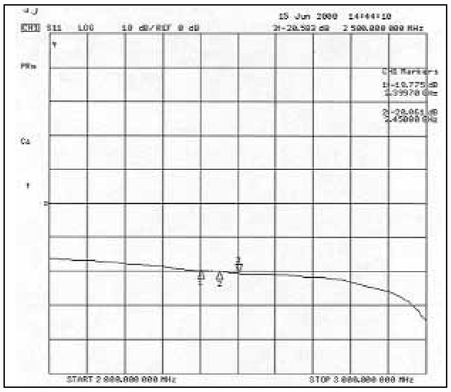
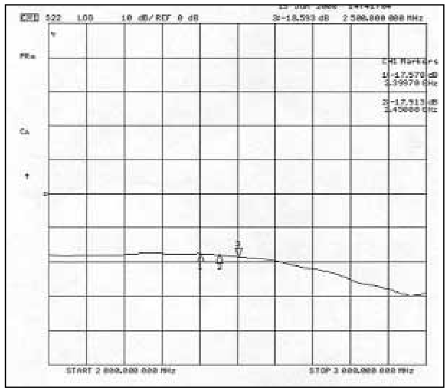
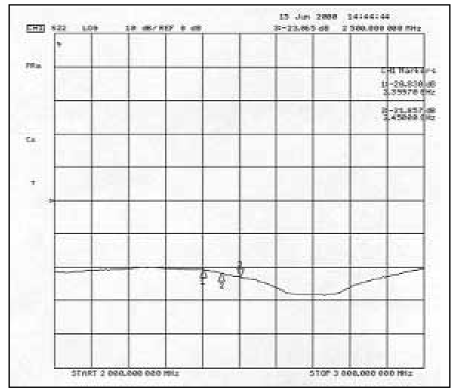


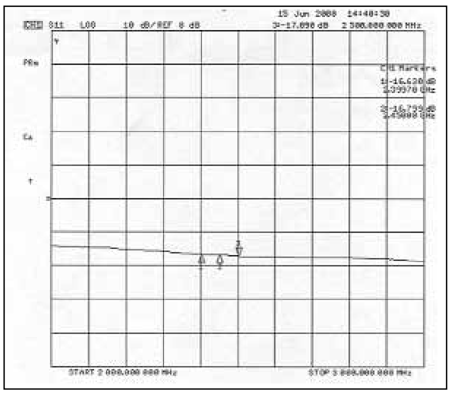
▲ **Input matching with IL = 30 dB.**



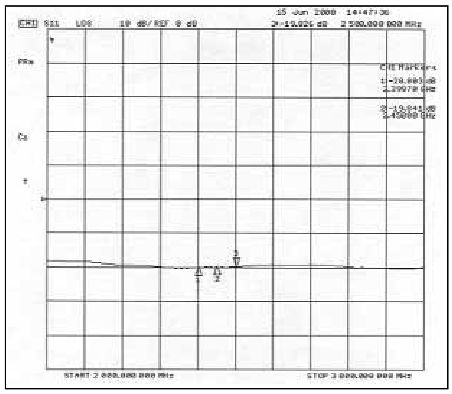
▲ **Output matching with IL = 20 dB.**



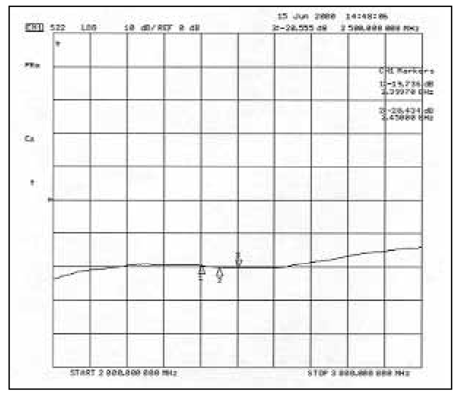
▲ **Output matching with IL = 30 dB.**



▲ **Maximum IL = 37 dB.**



▲ **Input matching with IL = 37 dB.**



▲ **Output matching with IL = 37 dB.**