Cut Part Count and Increase Dynamic Range in the Hybrid Coupled Attenuator

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Circuit design, component choices and better understanding of the variable element contribute to improved performance of this familiar attenuator

Topologies commonly used for implementing constant impedance attenuators include: Pi (π), Bridged-T, Resistive Line and Hybrid Coupled [1]. The attenuation can be made variable by replacing the resistive elements with either FETs or PIN diodes. PIN diodes behave like current-controlled resistors above ten times the cut-off frequency (f_c) given by

$$f_c = \frac{1}{2}\pi\tau$$

where, τ is the minority carrier lifetime. The diode junction resistance, R_j, can be varied by the application of different values of bias current. Generally, narrowband configurations like the Hybrid Coupled Attenuator (HCA) have substantially less phase change over attenuation compared to the wideband types such as Pi and Bridged-T [2]. Attenuators with minimal phase variation are usually required in phase-sensitive digital modulation formats.

Application Background

The heart of this attenuator is the microwave structure known as the hybrid coupler. It is also variously known as the quadrature hybrid, 3-dB hybrid and 90° hybrid [3], and can take shape in either lumped or distributed form. The hybrid coupler has four ports: input, direct, isolated and coupled [4]. The variable resistive elements, consisting of PIN diodes, are connected to the latter two ports. The effective resistance (R_d) of the PIN diodes can be varied by changing the bias current I_F [5]:
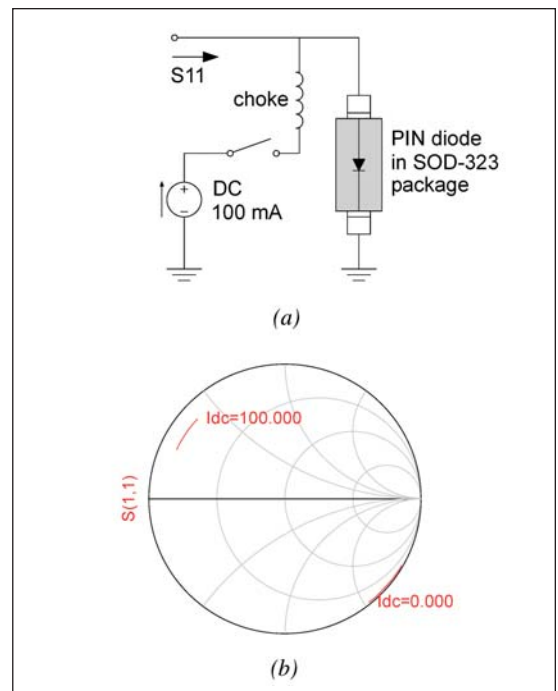

Figure 1 · (a) PIN diode impedance measuring circuit and (b) impedance of a SOD-323 packaged PIN diode at 0 and 100 mA bias current.

$$R_d = \frac{W^2}{2\mu I_F \tau}$$

where W is the PIN diode's I-layer height, μ is the ambipolar mobility of electrons and holes, and τ is the minority carrier lifetime.

In the HCA, the RF signal is the PIN diodes can be connected either in series or shunt to the load resistors (R1 and R2 in Figure 3). The shunt configuration is preferred when low attenuation values are required. For a given equivalent series resis-
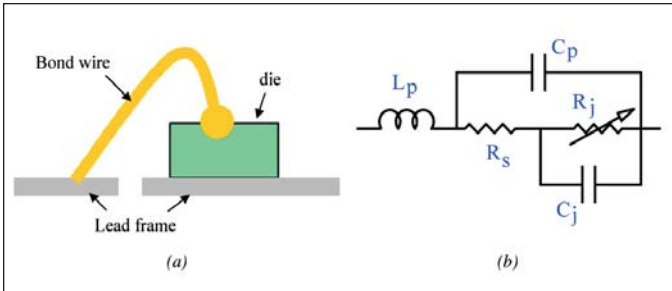
Figure 2 · (a) Interconnections inside a PIN diode package; (b) its equivalent circuit.

tance (R_j) of the PIN diode, the resultant attenuation for the shunt configured HCA is governed by [6]

$$A(dB) = 20\log\left(1 + \frac{2R_j}{Z_0}\right)$$

Concisely, the HCA achieves minimum attenuation (A_{min}) when the shunt diodes' resistance is close to zero (PIN diode in unbiased state) and maximum attenuation (A_{max}) when the resistance is highest.

Unfortunately, packaging changes the PIN diode's impedance at high frequencies and makes it deviates from a pure resistor. Modern plastic packages are highly popular because of their low cost and amenability to high-speed automated test handling. However, industry-standard plastic packages such as the SOD-323 has especially severe parasitics compared to traditional packages for microwave diodes such as the beam-lead and strip-line [7]. When the bias current is changed from zero to a high value, the diode impedance should ideally change from nearly open circuit to nearly short circuit; that is, the trajectory lies along the zero reactance line. In practice, however, the impedance trajectory of the SOD-323 packaged PIN diode moves from capacitive to inductive hemisphere when bias current is changed from 0 to 100 mA (see Figure 1).

Connection from the package lead to the PIN diode die is made using a bond-wire, as shown in Figure 2. For example, the SOD-323 package's bond-wire adds ~1.2 nH of stray inductance (L_p) in series with the diode's resistance. So, the PIN diode impedance appears inductive at forward bias. Conversely, the unbiased PIN diode appears like a very large resistance in parallel with a capacitor formed out of the die and package parasitic capacitances (C_j and C_p)—the contribution of L_p is negligible in relation to the impedance of the parallel RC.

When the biased PIN diode should ideally present a short circuit to the hybrid coupler, the residual inductance raises the effective impedance, thereby degrading the HCA's minimum attenuation. Waugh et al showed an innovative scheme to cancel out the PIN diode's parasitic
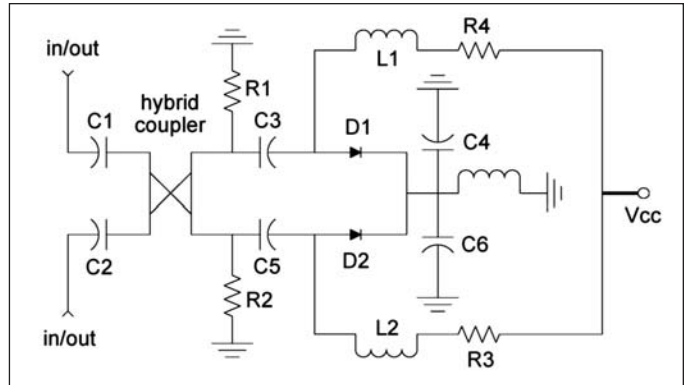

Figure 3 · Hybrid coupled attenuator after Waugh et al.

inductance and to restore the HCA's dynamic range [8]. His compensation scheme used two external capacitors (C4 and C6) as the RF ground for a pair of HSMP-3814 PIN diodes. The values of C4 and C6 are chosen to series resonate with L_p at the specified frequency of operation. Another two capacitors, C3 and C5 provided DC blocking to the PIN's bias current. The frequency selective resonant network will reduce the useable bandwidth, but this should not be a problem for cellular base-stations which are the expected primary users of HCAs.

Component Count Minimization

The roles played by RF grounding/resonating capacitors (C4 and C6 in Figure 3) and the DC blocking capacitors (C3 and C5) can be merged to save two components. Subsequently, the PIN diodes' cathode terminal can be directly grounded, as shown in the improved design of Figure 4.

Dynamic Range Improvement

The difference between the maximum and minimum attenuation levels constitutes the dynamic range (DR) of the HCA. In applications where the signal amplitude must be varied over a large range, the attenuator's DR becomes a critical parameter. Although the overall DR
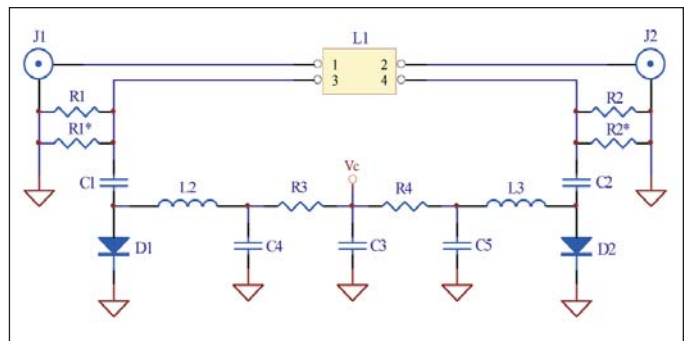

Figure 4 · New HCA design where one pair of capacitors (C1 and C2) play the dual role of parasitic cancelling and DC blocking.
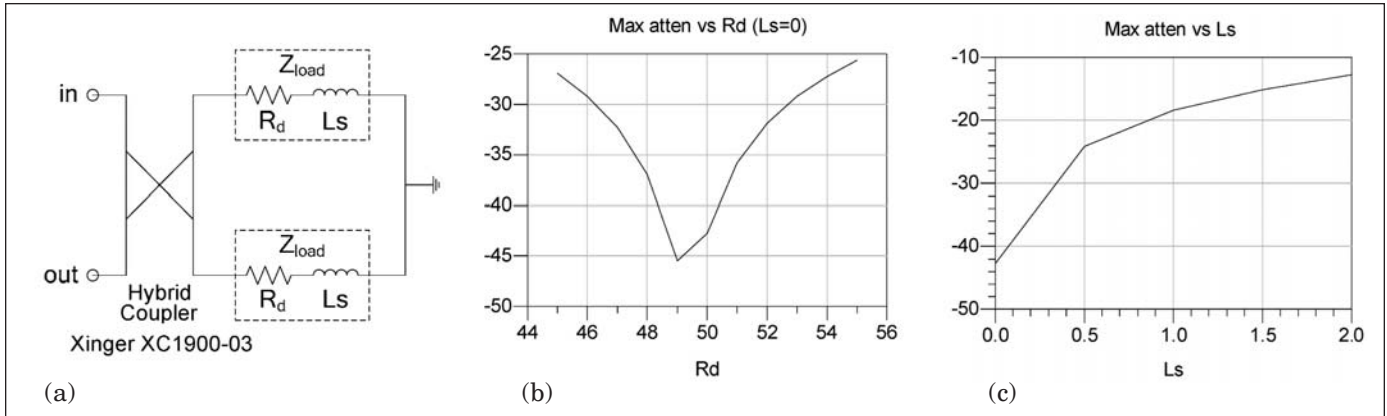
Figure 5 · (a) Simplified circuit of the HCA, **(b)** maximum attenuation vs. termination resistance Rd when simulated using Anaren Xinger XC1900E-03 hybrid coupler, **(c)** simulated maximum attenuation vs. parasitic inductance L_s in the termination.

can be doubled by cascading an identical attenuator stage, this may be prohibitive in term of cost or space requirement. So, the designer is often compelled by economic necessity to extract as much DR as possible from a single attenuator stage. The DR can be widened by increasing the maximum or reducing the minimum attenuation.

Factors that impose a limit on the HCA's A_{max} include:

1. Hybrid coupler's finite isolation (*Iso*)
2. Non-zero reflection coefficients at the "coupled" and "isolated" ports, and
3. Imperfect tracking between the adjustable resistive elements (e.g. PIN diodes).

The hybrid coupler's finite isolation imposes a practical limit to the A_{max}. The isolation is defined as the ratio of power at the input port to the isolated port

$$Iso_{lin} = \frac{P_{input}}{P_{isolated}} \quad or \quad Iso(dB) = 10\log\frac{P_{input}}{P_{isolated}}$$

Restricting our discussion to consumer grade surface mount hybrid couplers, the isolation generally scale with the physical dimensions (see Table 1). So, specifying a higher isolation hybrid coupler for the purpose of improving the A_{max} is sometimes not a viable option due to either size or cost constraint.

The A_{max} state of the HCA corresponds to zero bias current in the two PIN diodes (D1 and D2). The unbiased

PIN diodes are at high impedance and so, they practically "disappear" from the HCA circuit (this is a simplification which ignores the diode's parasitic capacitance which may be considerable at microwave frequency). Only the fixed resistors (R1 and R2) are left behind to terminate the hybrid coupler's "coupled" and "isolated" ports; i.e. the ports are presented with reflection coefficients very close to zero. The isolating property of the hybrid coupler is very dependent on the quality of the terminations at the "coupled" and "isolated" ports. In theory, the maximum attenuation will equal the hybrid coupler's specified isolation when the terminating impedances (Z_{load}) approximate a pure 50Ω resistor, i.e. Γ = 0. Achieving A_{max} = *Iso* is difficult in practice due to component parasitic in both the fixed and variable resistive elements and the biasing circuit. Working with standard surface mount resistors for the fixed resistive elements, a combination of circuit design and judicious component selection can minimize the reflection coefficients of the terminations.

The mis-tracking between the two variable resistive elements in a HCA can be reduced by using matched PIN diodes. The traditional method of hand-matching diodes from unrelated wafers (e.g. comparing the forward voltage, V_f, at 1 mA of bias current) generally yields inferior results as the DC parameters may have little relation to the RF characteristics. A better method of diode matching is to pick two PIN diodes from adjacent dices on the same wafer; since the diodes undergo same semiconductor processing, chances are their impedances will mirror each other at different biasing currents and preferentially also over temperature [11]. There are two convenient ways to obtain a matched diode pair from Avago Technologies: (a) specifying a part number consisting of dual diodes in one package (e.g. either HSMP-3814 or HSMP-381F) or (b) picking consecutive parts from one carrier tape (during the "in-line matching" manufacturing process [12], the

Size L × W × H (mm)	Typical isolation (dB)
2.0 × 1.6 × 1.0	19 [9]
14.2 × 5.1 × 1.8	40 [10]

Table 1 · Size and isolation of two commercially available surface-mount hybrid couplers for 1.9 GHz.
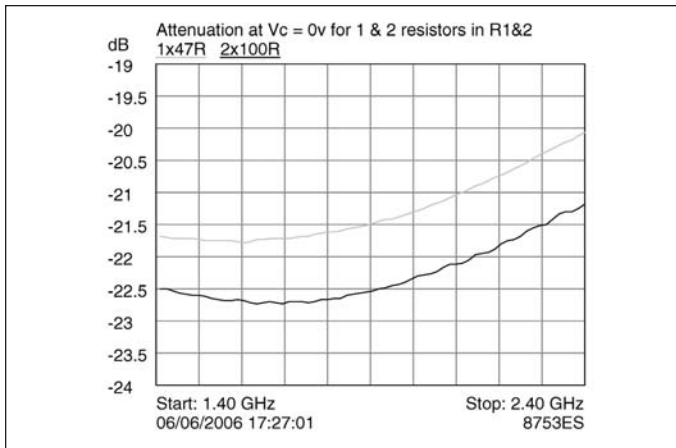
Figure 6 · A comparison of single (1×47Ω) vs. dual (2×100Ω) chip resistors in the positions R1 and R2 on the max. attenuation (diode OFF, control voltage Vc = 0V).
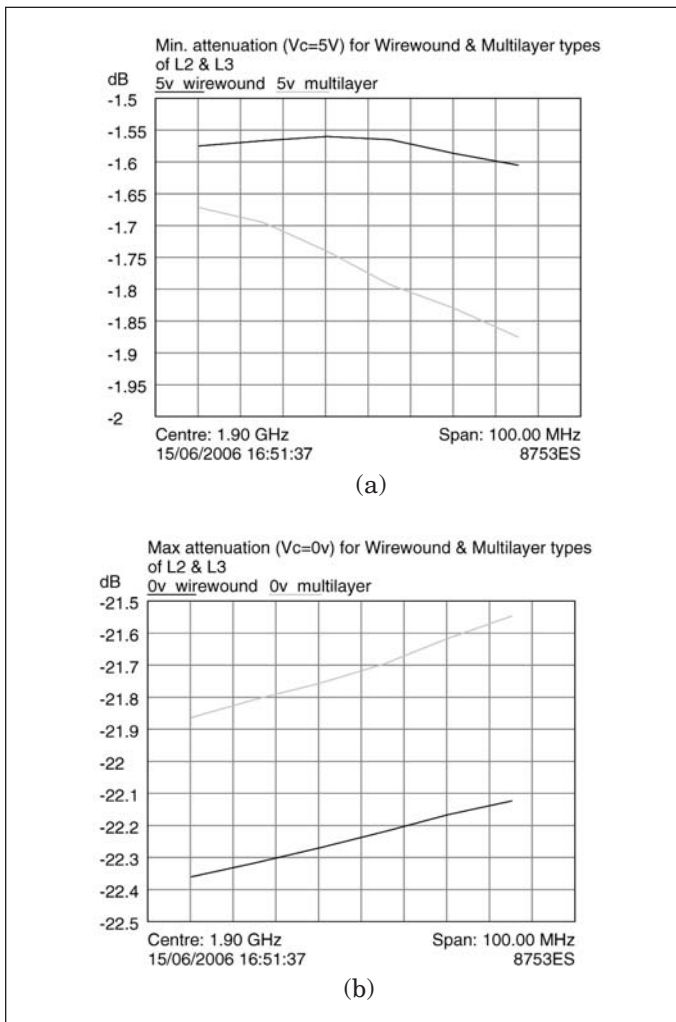

(a)

(b)

Figure 7 · A comparison of wire-wound (Toko LLQ1608) vs. multilayer (Toko LL1608) chip inductor in positions L2 and L3 for: (a) A_{min} and (b) A_{max}.

adjacent diode dice are placed sequentially on leadframe, then subsequently, singulated and arranged in the same order along the carrier tape).

An ideal HCA would have zero loss at A_{min}. However, the A_{min} of a practical HCA is limited primarily by how perfectly the forward biased PIN diodes can approximate a short circuit. The two series parasitics L_p and R_s in Figure 2(b) prevent the PIN diode from achieving zero impedance at maximum forward bias. Additionally, losses in the quadrature hybrid and the biasing circuit also increase the overall loss.

In order to present non-reflective terminations for the "coupled" and "isolated" ports, the resistors R1 and R2 are of the same resistance value as the characteristic impedance of the hybrid coupler (i.e., R1 = R2 = 50Ω for the Anaren Xinger XC1900-E03). At microwave frequencies, the parasitic reactances of these resistors degrade their reflection coefficients beyond what is predicted by the resistive real part. The chip resistors that are used to implement R1 and R2 can be thought as a complex combination of inductive and capacitance elements; though, for values less than 120Ω, the inductive component predominates [13]. The inductive parasitic in the positions R1 and R2 can be beneficially halved by using two 100Ω resistors in parallel (e.g., R1 in parallel with R1*) instead of a single 50Ω resistor. For a 1.9 GHz HCA design, the additional resistor translates into an improvement in the A_{max} that is close to one dB (Figure 6). Nevertheless, there is a limit to the number of resistors that can be added in parallel using this trick—using more than 2 resistors in R1 or R2 is not recommended because a resistance greater than 120Ω is primarily capacitive [13] and the parasitics will add up when connected in parallel. For lower frequency design (<1 GHz), adding R1* and R2* is unnecessary as the reactance of the parasitic inductance is insignificant.

Referring to Figure 4, the bias current for the PIN diodes is supplied through the inductors L2 and L3 by the application of a 0 to 5V control voltage at the terminal marked as "Vc." These inductors prevent the RF signal from leaking through the biasing networks by presenting a high reactance path at the operating frequency. At A_{min} (diodes fully turned ON), any leakage through the bias networks will further increase the RF signal loss. Conversely, at A_{max} (diodes totally OFF), the inductors serve to isolate the biasing networks from the "coupled" and "isolated" ports. Without sufficient isolation, the bias networks will degrade the reflection coefficients at these ports and consequently, worsen the A_{max}. The physical construction of an inductor determines its high frequency characteristics such as the parasitic capacitance, the unloaded Q and the Self Resonance Frequency (SRF). Generally, these attributes are more favorable in wire-wound inductors than in multilayer ones. When wire-

wound (Toko LLQ1608) or multilayer (Toko LL1608) chip inductors are compared in positions L2 and L3 (Figure 7), there is a noticeable difference in the A_{max} (Vc = 0V). They also have an effect on the A_{min} (Vc = 5V), albeit less significantly. For these reasons, wire-wound inductors should be used whenever greater dynamic range is desired.

Conclusion

Part count in a previously published HCA design can be reduced by combining the functions of the DC blocking and parasitic cancelling capacitors. A practical 1.9 GHz HCA implementation based on this component-reduced design was shown. Additional techniques to improve the DR by means of skillful component selection were also discussed. Future work lies in closing the gap between the currently achievable A_{max} and the hybrid coupler's much higher raw isolation.

Acknowledgement

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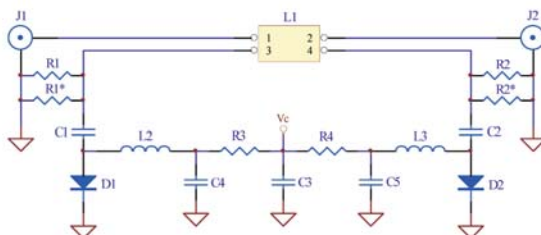
	Value	Size	Description
C1	2.2 pF	0603	Murata GRM18
C2	2.2 pF	0603	Murata GRM18
C3	1 nF	0603	Murata GRM18
D1	Hsmp-381Z	SOD-323	Avago Technologies
D2	Hsmp-381Z	SOD-323	Avago Technologies
J1	Edge Launch SMA connector		Johnson 142-0701-881
J2	Edge Launch SMA connector		Johnson 142-0701-881
J3	2 pin header		
L1	3 dB Hybrid Coupler		Xinger XC1900E-03
L2	47 nH	0603	Toko LLQ1608
L3	47 nH	0603	Toko LLQ1608
R1	100Ω	0603	
R1*	100Ω stacked above R1	0603	
R2	100Ω	0603	
R2*	100Ω stacked above R2	0603	
R3	39Ω	0603	
R4	39Ω	0603	

Table 2 · Parts list for the improved 1.9 GHz HCA of Figure 4