VVA Extends BW And Dynamic Range

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VOLTAGE-VARIABLE ATTENUATORS (VVAs) ideally provide amplitude control over a broad frequency range with high repeatability and accuracy. In addition, with modern pressures for miniaturization in electronic products, they should do so in the smallest package possible. What follows is the backstory of how a diode-based pi attenuator was developed with wide bandwidth and high intercept point in a compact package measuring only 3.8 x 3.8 mm. The VVA serves a wide range of applications, including in cable-television (CATV), satellite-television (SATV) systems, and even test equipment.

In spite of the half-dozen or so topologies for realizing a constant-impedance VVA, only the pi (π) and T topologies result in reasonably small components in the 10-to-500-MHz range. In addition, the pi and T configurations are broadband since they do not rely on frequency-dependent components such as transmission lines, quadrature hybrids, or circulators. As a result, these topologies can yield small components capable of continuous coverage from a few MHz to several GHz. In particular, the pi VVA configuration is popular in CATV and SATV systems owing to its low cost, small size, and wide bandwidth.

PIN-diode-based pi attenuators, not unlike other components used in wireless applications, have been under pressure to be made smaller to save space in end-products. Figure 1 plots the occupied area of several generations of this VVA class; the linear trend-line estimates a size erosion rate of about 20 mm square per year. In one of the earliest attempts at miniaturization for this class of attenuator, three PIN diodes were integrated into a DIN 50B4 pill package to create the Intermetall TDA 1053. However, the 1960s-era three-diode topology was excluded from Fig. 1 because it has been largely supplanted by the 4-diode version introduced by Waugh in 1991. The Waugh design quickly became the de facto standard because it eliminated the asymmetric bias problem inherent to the three-diode topology. It also represented a milestone in the VVA miniaturization chronology because it introduced an all-surface-mount construction. Subsequent attempts at miniaturization were accomplished by implementing the diodes as 2 x SOT-323, integrating the diodes and other passive components into an IC, and integrating all four diodes into one SOT-89 package. The monolithic route of size reduction is not available because nF-range capacitors are required for the attenuator to work down to the 5 MHz lower frequency limit of the CATV upstream path. The significance of this design lies in it being the smallest in class at the time of design (2008). The module occupies a footprint of 14 mm square which represents only 4% of the area of the first four-diode implementation.

**1.** Over time, the size of PIN diode pi variable-attenuator modules has shrunk consistently in keeping with the demands of broadband applications, including CATV and SATV.

**2.** This design is a basic pi fixed attenuator along with its design equations.
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3. These plots compare the second- and third-order intercept points (IP2 and IP3) of PIN diodes with two different values of carrier lifetime, $\tau$.

4. By replacing the fixed attenuator in the basic pi design by two diodes, a variable attenuator is created.

diode topology. The circuit symmetry guarantees identical bias currents through the shunt diodes. Implementing the series arm as a pair of opposing diodes (anti-series pair) also reduces second-order distortion because the nonlinearities are 180° out-of-phase and will cancel out each other.

The diodes’ bias current and, consequently, the attenuation are controlled by voltage $V_c$. Resistors R1 and R2 serve as bias returns for both series and shunt diodes. Since these two resistors shunt the RF path, their resistances should be high enough to block RF, but not so high that there will be large DC voltage drops across them. The current through the shunt diodes is supplied by a fixed voltage, $V_c$, and is limited by resistors R4 and R5. In this design, a $V_c$ of +1.5 VDC was empirically determined to give the best return loss at all attenuation values.

The four-diode VVA was originally designed for the control voltage to be varied from 0 to 15 V. Since modern electronic products are limited in voltage supply, an operating requirement that exceeds 5 V will considerably shrink the pool of prospective customers. But capping the highest $V_c$ value at 5 V has the adverse effect of increasing the minimum attenuation from 3 dB to 9.5 dB (at 1 GHz), owing to the reduction in the maximum current available for biasing the series diodes.

To achieve similar minimum attenuation as the original, but at one-third of the control voltage, this design uses smaller values in R1-R3 to permit greater current flow through the series diodes. Resistors R1 and R2 were reduced by about 42% (from 560 $\Omega$ to 330 $\Omega$) and R3 by over 93% (330 $\Omega$ to 22 $\Omega$). However, these resistors shunt the RF path, and making their resistances smaller than four times the characteristic impedance ($4Z_0$, or e.g. R < 300 $\Omega$ for a 75-$\Omega$ system) will reduce their effectiveness as RF
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chokes. The RF loss via R3 is especially severe because $R_3 \ll 4Z_o$. To compensate for R3’s reduced choking capability, a ferrite bead inductor L1 is added in series with R3 to increase the effective impedance. A ferrite bead inductor was chosen over a conventional inductor because the former is more effective for broadband choking. A total of four PIN diodes, six resistors, five capacitors, and one ferrite bead inductor were integrated into a standalone VVA module measuring 3.8 x 3.8 mm. The components were assembled Multi-Chip-On-Board (MCOB) style on a 10-mil-thick Roger RO4350 printed-circuit board (PCB) laminate from Rogers Corporation (www.rogerscorp.com) with relative dielectric constant, $\varepsilon_r$, of 3.48, and dissipation factor of 0.004. Viaholes link the top-side circuit traces to the bottom-side pads for DC and RF connections. The component side is then molded over to achieve a 1-mm package height.

The experimental results confirm that the target bandwidth, operating voltage, and linearity specifications can be met using this design. VVA module testing was centered on the CATV/SATV frequency ranges because these were the target market segments. The test fixture (Fig. 5) comprises 50-Ω microstrip traces (transmission lines 1 and 2, TL1 and TL2) on RO4350 PCB. TL1 and TL2, which connect to the device-under-test (DUT) input and output pins, respectively, are approximately 10.6 mm long each. The microstrip ends at the PCB edges are transitioned to coaxial by edge-mount SMA receptacles, J1 and J2 (model 142-0701-851 from Johnson Components (www.futureelectronics.com)).

The frequency response and attenuation range were measured by connecting the fixture to a commercial microwave vector network analyzer (VNA) (Fig. 6). Voltage $V_c$ was swept from 0.5 to 5 V to produce different attenuation values versus frequency (Fig. 7). The response is extremely flat with frequency: the attenuation changes less than 3 dB from 0.1 to 6 GHz for values of $V_c \geq 1.2$ V, and if the evalu-
The PIN-diode-based VVA evaluated frequency range is constrained to 50 to 2050 MHz as in CATV/SATV applications, the amplitude variation is less than 1 dB. However, the flat attenuation characteristic cannot be maintained at lower control voltages (e.g., $V_c \leq 1.0$ V) because the series diodes turn off at this low volt-

age and the RF signal could leak through the diodes’ parasitic capacitance. As the parasitic capacitive reactance is inversely proportional to frequency, the attenuation curve at $V_c = 1.0$ V assumes a frequency dependency and so changes at a 6-dB/octave rate. The range over which the attenuation can be varied is greatest at low frequency (more than 55 dB at 100 MHz) and progressively less at higher frequencies—e.g., about 30 dB at 6 GHz.

Figure 8 shows attenuation versus $V_c$. There is hardly any change in attenuation for $V_c$ below 1 V. Above 1 V, the attenuation changes rapidly with $V_c$, flattening out above 2 V. Although it appears from Fig. 8 that the attenuation has stabilized above 2 V, there is a worthwhile change of about 2 dB between 2 and 5 V. At $V_c = 5$ V, the attenuation reaches a final value of approximately -4 dB and this value is relatively stable from 0.3 to 3 GHz as apparent in the overlapping curves. So, the usable $V_c$ range is 1 to 5 V. The concentration of most of the attenuation variation in the 1-to-2-V range is an unavoidable tradeoff arising from compressing the control voltage range from 15 to 5 V.

The input third-order intercept point (IIP3) changes with attenuation (Fig. 9). The resistances of the series and shunt arms change in opposite directions—i.e., at large attenuation values, the series arm’s resistance is high whereas the shunt diodes’ resistances are low. So, the poorer IP3 at large attenuation is due to a greater proportion of RF current being dumped into the input-side shunt diode and adversely modulating its 1-layer. The IIP3 improves with higher operating frequencies (better at 1.9 GHz than 900 MHz). Within a 40-dB attenuation range, IIP3 is better than +52 dBm. In comparison, the IIP3 of a MESFET pi attenuator varied from -2 to +14 dBm over the same attenuation range—i.e., about 50 dB.
In summary, a self-contained PIN diode pi attenuator module was designed and implemented. Key challenges were attaining high linearity and operating at a low control-voltage range. Using MCOB construction, all necessary components were integrated into a 3.8 x 3.8 mm area, thereby setting a new benchmark for miniaturization in this device class. After packaging in low-cost plastic molding, the module exhibited exceptional RF performances in gain flatness and linearity, including besting the IP3 of a MESFET-based equivalent by over 50 dB. The attenuation can be varied over 45 dB in the 50-to-1950-MHz CATV frequency range, and over 30 dB from 5 MHz to 6 GHz. Although CATV/SATV systems were the target applications, the attenuator’s three-decade bandwidth extends its usefulness to products such as test instruments and scanning receivers.

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