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## Variable 6 – 60dB 500MHz RF Attenuator

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Variable RF attenuators are a frequently used piece of test equipment. This is a description of two versions of a continuously variable RF attenuator suitable for many RF applications on the test bench.

### Introduction

When I designed my [DDS-based HF/VHF AM/FM signal generator](#) several years ago, one of the critical sections of the design was the variable attenuator. In that design, I used a combination of four 20dB switched attenuators along with a Serebriakova 6 - 15dB variable attenuator.

While the final result was satisfactory, the DPDT slide switches became unreliable after several years of intensive use. In addition, the Serebriakova variable attenuator, one part of the multi-section attenuator, did not provide a particularly good match for 50 ohm systems at certain settings. Occasionally, some load-sensitive RF amplifiers being tested with that signal generator did not take kindly to that.

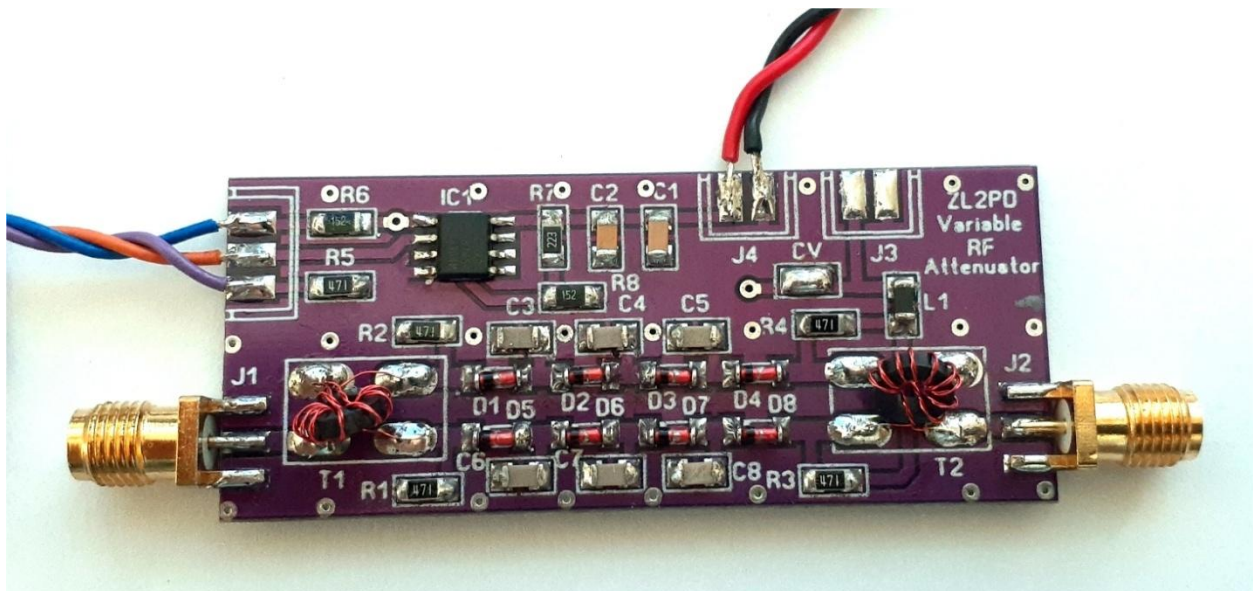


Figure 1 : Testing the prototype attenuator in a cheap entry-level RF signal generator

Recently, I decided to look at the design of a variable RF attenuator once again. In part, it was driven by the purchase of a cheap 85kHz to 40MHz basic RF signal generator at a local ham club auction.

That signal generator featured a simple variable resistor and switched resistor attenuator arrangement which is fairly typical of such generators. This has limited range, high RF leakage at low output levels, and a very non-linear output level as the output level panel control was rotated. In use, most of the change in attenuation occurred within a very narrow range of the level control's rotation.

## Variable RF Attenuator Solutions

Going back to basics, I looked at the types of RF attenuators that I could build in my workshop. I identified a number of different variable RF attenuator categories during my search. These included:

- **Switched resistor attenuators** – Relay or manually switched fixed attenuators typically arranged in Tee or Pi resistor attenuator networks. These are routinely seen in articles and on the internet. Switch and relay isolation can be a problem unless components are carefully chosen and tested, and some relay attenuators can be surprisingly noisy in use. Eventually, both switch and relay attenuators can become unreliable over time.
- **Integrated circuit attenuators** – These appear basically to be a solid state variation of the previous category. Typical examples (e.g. PE4302, HMC472 etc) provide up to 31dB attenuation in steps of 0.5 or 1 dB over wide RF bandwidths. They provide a flat response up to 2GHz but this can be a relatively expensive solution if, say, 60 - 90dB of variable attenuation is required. RF power through these chips is usually limited to about +20dBm although some will (briefly) manage 30dBm (1W). With three in series, the insertion loss can be relatively high.
- **Serebriakova variable attenuator** – The attenuation adjustment range is limited to about 15dB. Continuously variable, this simple resistor attenuator network also has a 6dB minimum insertion loss. The attenuator can operate at RF power levels of several watts.
- **Piston “waveguide-beyond-cutoff” attenuators** – These are extremely accurate wide bandwidth attenuators easily capable of more than 120dB of adjustment range. Relatively large and mechanically challenging to make and use, they also have a very high insertion loss. These can be used at both low and high RF power levels.
- **Active Tee attenuator** – Limited range continuously variable attenuator with typically 6 - 18dB attenuation. Simple to make but the limited range requires additional attenuators using relays or switches be used if an attenuation range of, say, 120dB, is required.
- **PIN Diode attenuator** – PIN diodes are usually arranged in modified Tee or Pi attenuator arrangements. These act like current controlled resistors at RF frequencies. The attenuation range is typically 6 – 25dB per stage, and they can give excellent results over wide bandwidths. However, they usually require additional relay or switch attenuators in most applications. Some PIN diodes can be expensive and hard to find.
- **Standard diode-based variable attenuator** – Standard silicon junction diodes can be used to provide a continuously variable attenuator with up to 60dB attenuation range.

Before I go into further detail on that last item in my list, I'll just deviate briefly to describe...

### Piston “Waveguide-beyond-Cutoff” Attenuators

Little known now, this RF attenuator was originally developed by the UK's Royal Signal Corp in 1942 with details being first published in November 1943. A more detailed paper by G F Gainsborough of the UK's National Physics Laboratory appeared in 1946. Other useful references include a VHF signal generator design using such an attenuator which was described by G W Sutton in the UK's Wireless World magazine in December 1967.

Here's the basic principle: If an RF signal is radiated through a metal tube at frequencies below the waveguide cutoff frequency of the tube (i.e. A frequency typically below several GHz for most small diameter metal pipes) then it turns out that *RF attenuation increases linearly with distance down the tube independent of signal frequency.*

Coupling the RF signal into and out of the metal tube is a key issue. The coupling can be inductive or capacitive. Published versions usually describe inductive coupling, but capacitive coupling is arguably easier.

I designed one of these capacitively coupled attenuators some years ago during my final year at university. It turns out the metal tube doesn't have to be particularly large. They are typically about 20 - 30mm in diameter and 100 - 200mm long. Figure 2 shows the basic arrangement.

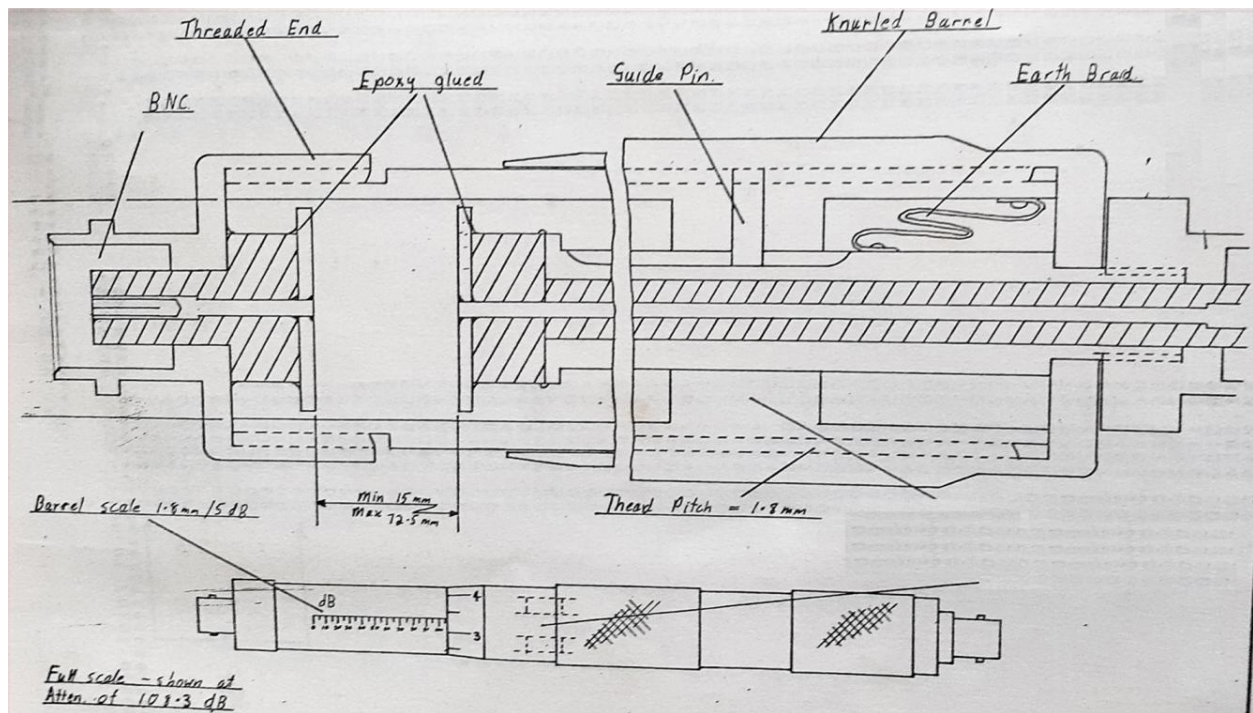


Figure 2 : This is a detailed sketch from my university notes of a capacitively coupled piston (or "waveguide beyond cutoff") RF attenuator made from a threaded 15mm ID plated copper tube .(Right-click on the image to see it full size) tube.

The mating external knurled barrel of the attenuator threads over the inner tube to allow attenuation adjustment. Each tube was fitted with, in this case, a BNC connector. The inner capacitive coupling plates are also carefully isolated from the tube walls by a small air gap.

These "piston" attenuators were widely used by the industry for about two decades after WW2. An example from that period can be seen in HP's HP-3200 VHF signal generator. While very accurate and precise, and capable of handling quite high RF power levels, using attenuators such as that shown in Figure 2 results in twisting of the connecting cables as it is adjusted, which is a significant problem. Other mechanical arrangement, such as that used in the HP-3200, proved equally problematic.

Ultimately, their large size, connectivity issues, and their high minimum insertion loss – typically 20 to 30 dB – eventually led to their rapid replacement by other types. Still, it represents an interesting attenuator, and the mathematics of the design were really interesting to derive back in the day.

## Standard Diode Attenuator

I decided to explore the standard diode variable attenuator option further after I stumbled across a brief paragraph or two in the design summary of the famous HP-8640 RF signal generator. It's found in the HP Journal of February 1973.

The article briefly noted a wideband modulator designed by HP's Ken Astrof which used a series of standard silicon diodes. The article claimed this circuit could provide up to 60dB of attenuation well into the UHF region. This stage was used for amplitude modulation and RF levelling in the HP-8640B signal generator.

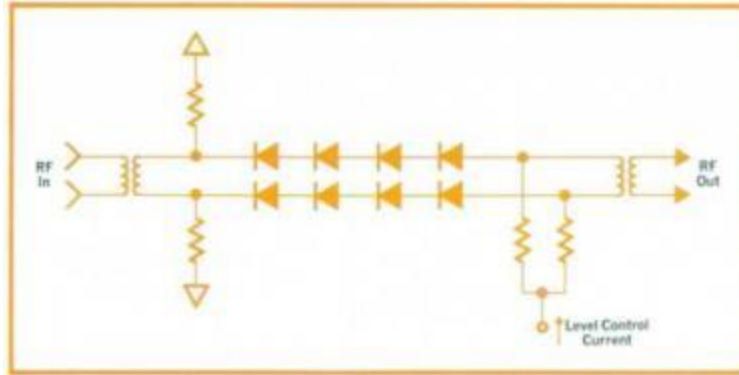


Figure 3: The diode-based modulator stage in HP's famous HP-8640 RF signal generator can deliver over 60dB of RF attenuation

I quickly lashed up a basic version of the circuit and ran some tests. Initial results suggested the claimed 60dB attenuation could be achieved. However, the control voltage required was a potential problem as was determining a suitable design for the coupling transformers.

You can see the control voltage that was required from the graph of the voltage/attenuation characteristics of diode attenuator section of one of my early prototypes (Figure 4).

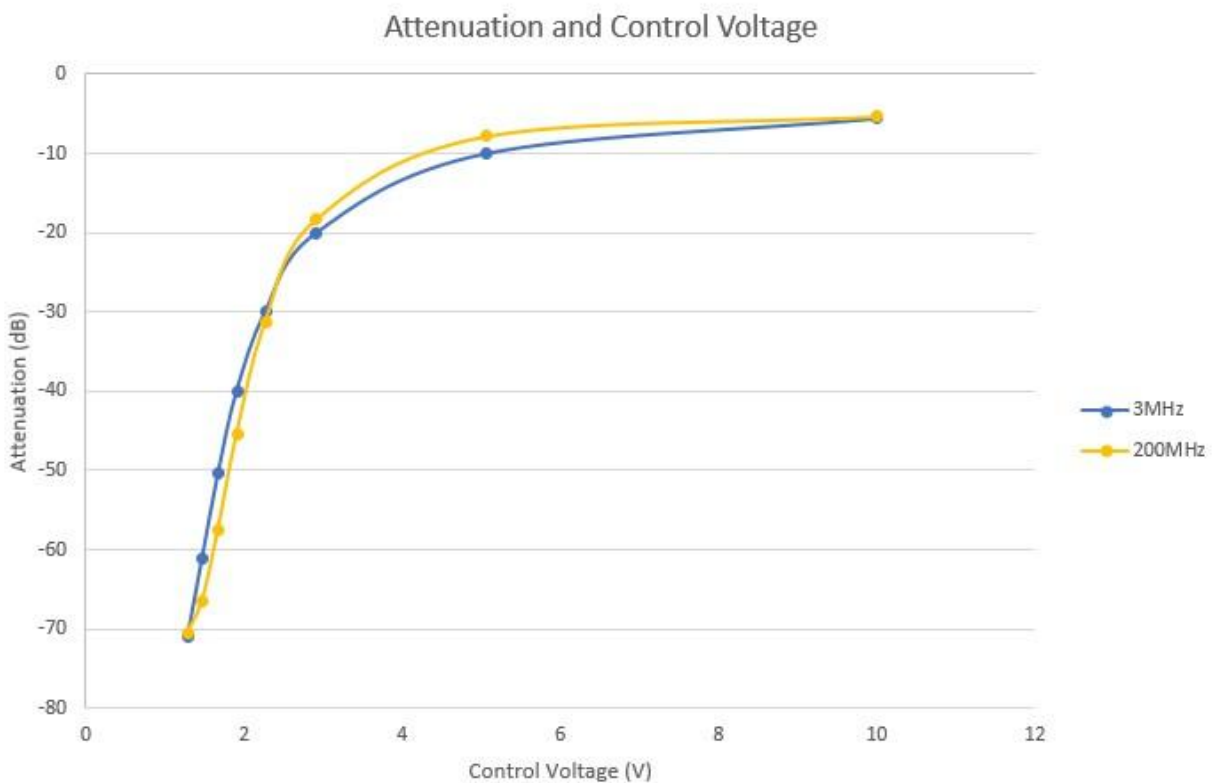


Figure 4 : The control voltage range of 1 – 3V gave the greatest change in RF attenuation which also appeared to give a reasonably consistent result at the frequencies of 3 and 200MHz initially tested

Clearly, most of the changes in attenuation occur in the control voltage range between 1V and 2.5V and, equally obviously, the overall characteristic is highly non-linear. That curve made ordinarily setting the attenuator to a specific value quite difficult.

I could have designed an up-market digital interface with an OLED display, an ATtiny25, and a simple digital-to-

analog converter to address this issue. I may still do that for another application. On this occasion, however, I wanted to keep the design as simple as possible to allow it to easily replace the existing attenuator in a typical cheap entry-level signal generator.

Let's examine that existing attenuator and measure its performance.

## A Typical Entry-Level RF Signal Generator

As mentioned earlier, I recently purchased a typical example of an entry-level signal generator. I got a very clean second-hand VIZ WR-50C at a local radio club auction for under \$US10. It covers from 85kHz to 40MHz and features both unmodulated and amplitude modulated RF output capability.



Figure 5 : The VIZ WR-50C is typical of low cost entry-level RF signal generators. Additional features here included a scanning function for IF alignment at 455kHz and 10.7MHz and a crystal checking function.

The WR-50C uses a pair of switched resistors and a variable resistor as the output RF attenuator, a standard arrangement typical in this type of instrument. See Figure 6.

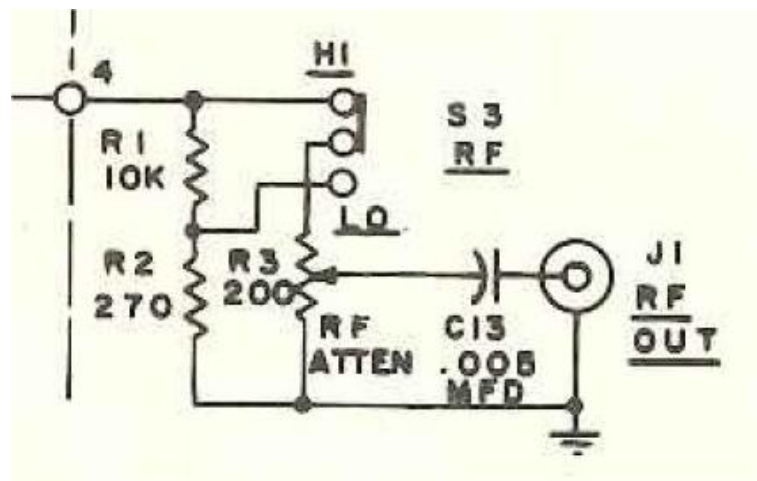


Figure 6 : The VIZ attenuator is a typical example of attenuators in entry-level signal generators. These have a limited range of attenuation and relatively poor isolation.

This network is mounted on and around the Hi/Lo level switch and attenuator adjustment variable resistor which are mounted directly on the front panel. The wiring to the generator PCB used relatively long unshielded runs of single core copper wire.

The signal generator specifications stated an unterminated maximum output of about 50mVrms (HI) or 500uVrms (LO) from the variable resistor. When I tested my generator, the 50 ohm terminated output levels were found to be those detailed in Table 1.

RF Switch	RF Atten	1MHz	3MHz	10MHz	20MHz	40MHz
HI	Max Out	-16 dBm	-14 dBm	-17 dBm	-18.5 dBm	-17.5 dBm
	Min Out	-70 dBm	-69 dBm	-63 dBm	-43 dBm	-44 dBm
LO	Max Out	-32 dBm	-29 dBm	-38 dBm	-42 dBm	-43 dBm
	Min Out	-80 dBm	-69 dBm	-59 dBm	-42 dBm	-41 dBm

Table 1 : Unmodified terminated RF output characteristics of the Wiz WR-50C RF signal generator

While the output is reasonably level across the generator's range, those with sharp eyes will have already spotted some major issues:

- The attenuator provides up to (about) 50dB of attenuation at 1MHz but that attenuation adjustment range falls to just 25dB at 40MHz
- Poor isolation in the attenuator and equipment construction limits the minimum output to about -70dBm below 3MHz, -60dBm at 10MHz, and just -40dBm from 20 to 40MHz
- Although not shown in the table, the attenuator adjustment was very non-linear

For example, at 20MHz and 40MHz, you can see that the maximum output on the HI setting is close to or less than the maximum output on the LO output setting! The minimum output from the variable attenuator on this LO setting at 40MHz, for example, is actually greater than when the output control is set for the maximum output level. This suggests the switch and variable attenuator arrangement is not providing adequate isolation at that frequency. Operation is marginal anywhere above 10MHz, actually.

I wanted to see if I could replace this ineffective arrangement with an improved variable RF attenuator. Ideally, I wanted an attenuator adjustment range from 1 to 40MHz of 60dB using the front panel RF Level control. The HI/LO switch might then be used to select another 30dB via a switched fixed attenuator. Ideally, this would give me up to 90dB of attenuation range.

However, in these cheap generators, the case shielding and power cable arrangement usually limits what can be achieved. The WR-50C is probably only able to support a range of about 60dB, so that was my objective here. In a better shielded signal generator, a 60dB variable attenuator might be combined with a pair of switched 20 and 30dB fixed attenuators to provide a total range of attenuation adjustment of over 100dB. Since the rotary panel mounted potentiometer was to be used to adjust the attenuation, the first step was to design a simple circuit to allow such a control to be used with the diode attenuator circuit.

## Designing a Better Attenuator Control

A bit of effort with a number of different prototype circuits ranging from a few discrete transistors to a handful of transistors and several op-amps ultimately resulted in the relatively simple arrangement shown in Figure 7.

T1, T2 : 10t / 10t on FB23-43 toroid

All diodes 1N4148 unless otherwise stated

All capacitors are 4p7 ceramic unless otherwise stated

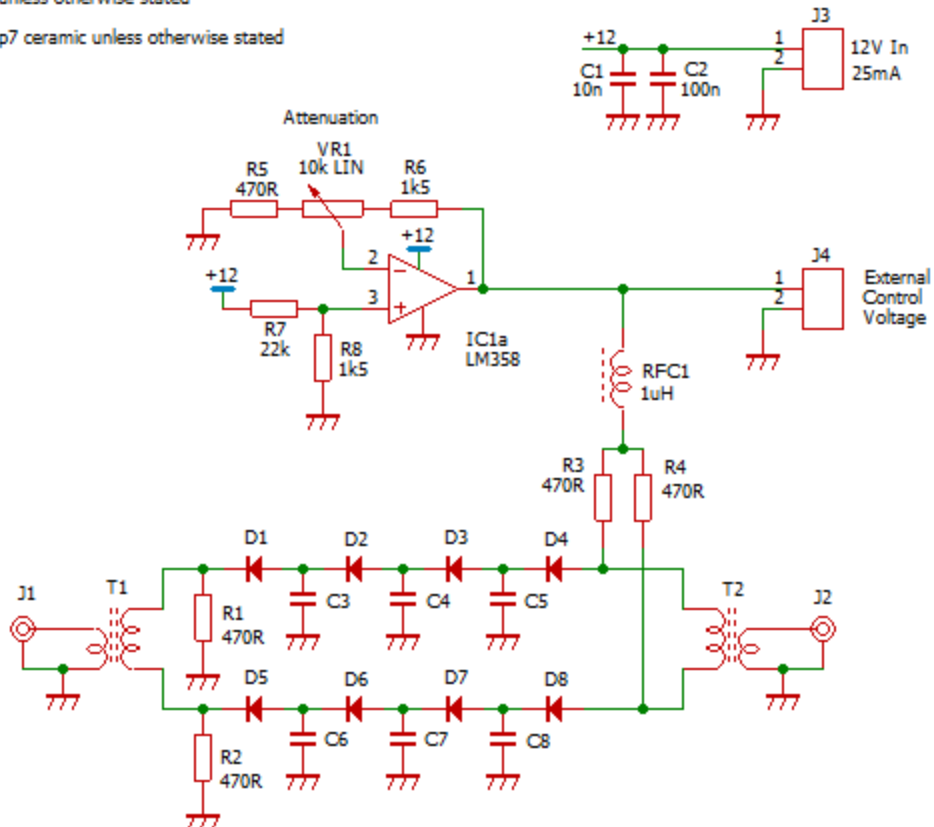


Figure 7 : Schematic of the variable 6 – 60dB RF attenuator

The diodes act as current-controlled variable resistors in a balanced pair of attenuators with R1 – R4. Ceramic capacitors C3 – C8 (All 4.7pF) provide additional attenuation with increasing frequency and improve the overall frequency response.

The circuit around IC1 delivered the modified attenuation characteristic shown in Figure 8. The resulting control is not only reasonably linear, but it also proved to be very easy to use in practice.

I built an improved version of the roughly wired prototype using a single sided PCB. This reduced the component lead lengths of the initial versions of my circuit and allowed for further testing. The results, along with a photo of this prototype, are shown below.

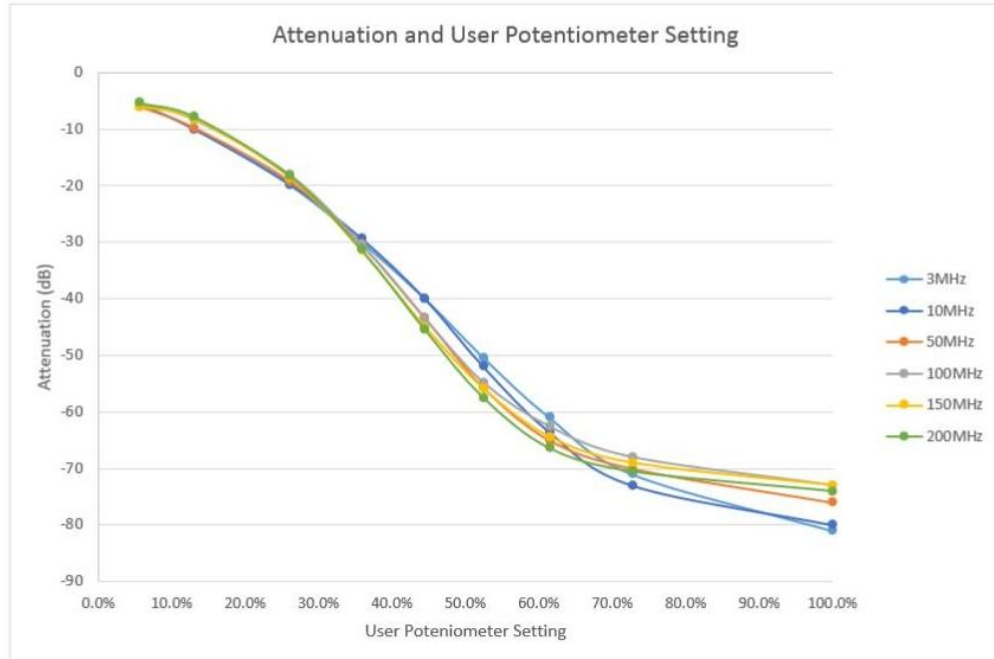


Figure 8 : The prototype on its simple PCB gave surprisingly good results from 3MHz to 200MHz. This version was built from standard leaded parts on a single sided PCB. This is shown in Figure 9 below.

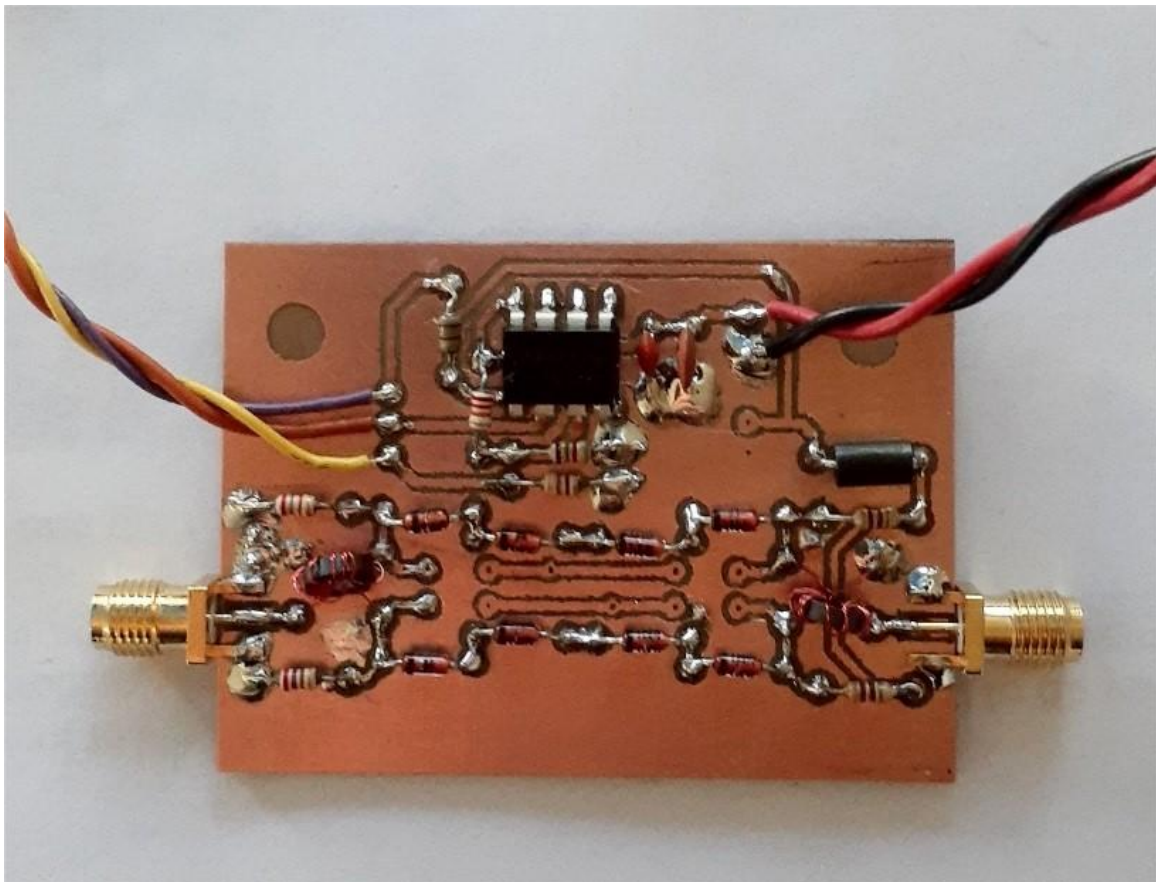


Figure 9 : Here is the prototype which used standard through-hole parts. This shows the board without the capacitors C3 – C8 which proved unnecessary in this version. It is constructed on an undrilled etched single-sided PCB to allow it to be directly mounted over a ground-plane surface such as an aluminium chassis or front panel.

As the graphs show (e.g. Figure 8, Figure 11), it proved suitable for use in basic applications for frequencies up to, say, 200MHz. It therefore appeared ideal to test as a replacement for the attenuator arrangement in the Viz WR-50C signal generator.

Here is the updated PCB layout for those wanting to try this simple arrangement.

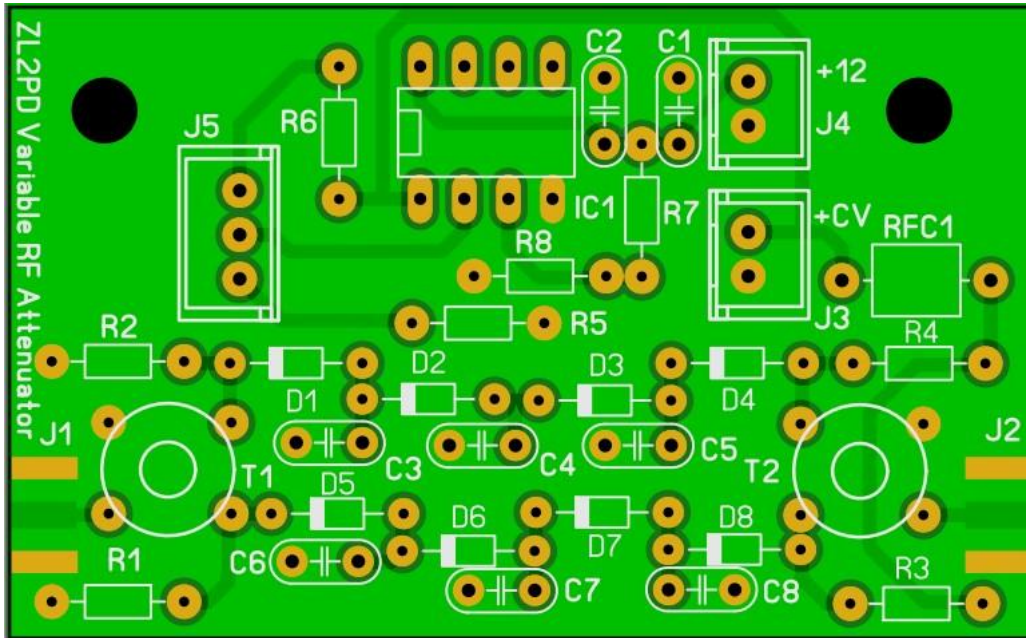


Figure 10 : Updated double-sided prototype PCB layout of the original single sided prototype PCB. This version provided an improved frequency response.

The performance of this PCB is plotted below for frequencies up to 300MHz (Figure 11) for a range of attenuation settings. The control voltage is the voltage applied to connector J3 with a supply to the op-amp via J4 of 12V.

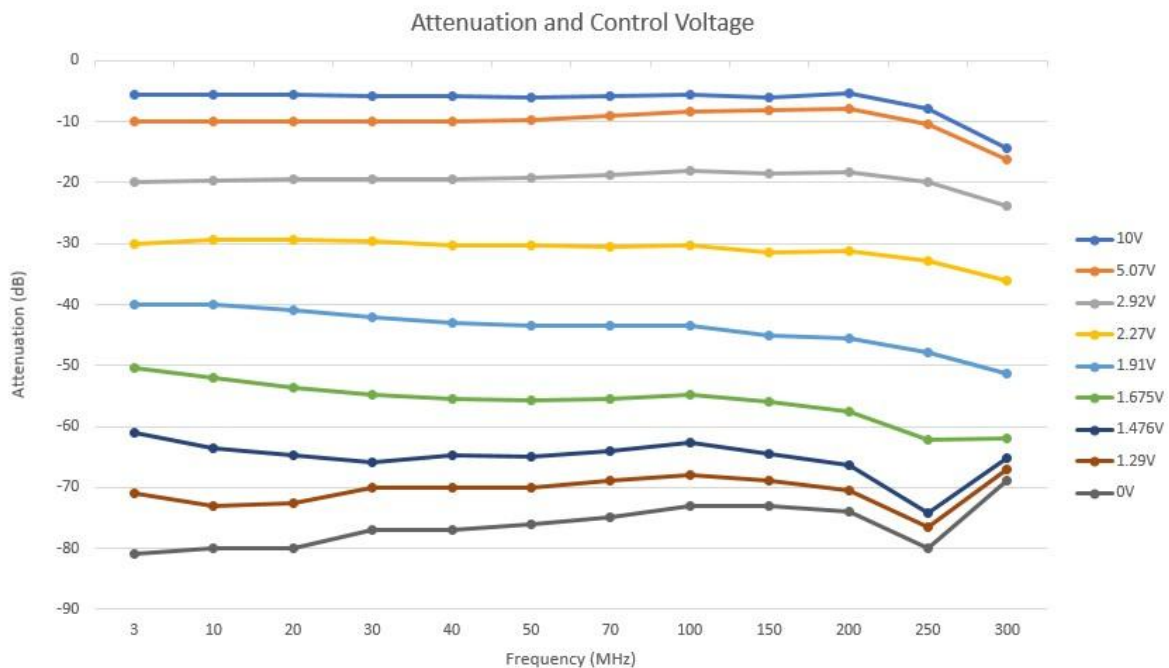


Figure 11: The attenuator response is measured into a 50 ohm termination from 3 to 300MHz.

This series of responses for the prototype was plotted based on setting the attenuator in 10dB steps at 3MHz. The response is reasonably flat to 200MHz for the initial 25dB pf attenuation. Across the plotted range, the attenuator can provide up to 70dB of attenuation adjustment up to 250MHz. Levelling with an external microcontroller can be readily achieved with this design.

The glitch at 250MHz at -60 to -80dB attenuation levels was probably due to the long component leads and PCB tracks on the prototype.

## Installation and Testing in Viz WR-50C Signal Generator

One of these prototype boards was fitted into the WR-50C in place of the existing attenuator potentiometer and switch network. 12V was obtained from the generator's regulated 15V supply via a 100 ohm resistor and 12V 400mW Zener diode regulator. It was not particularly pretty. I just wanted a simple arrangement to test the principle.

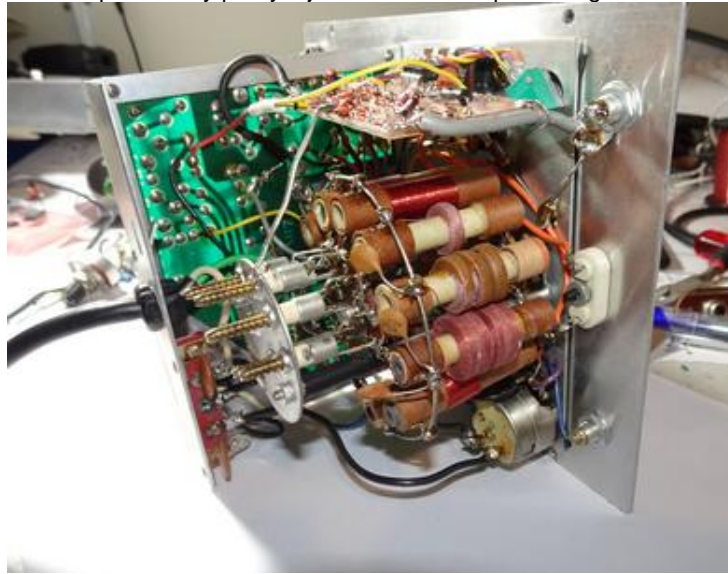


Figure 12 : The attenuator was installed into a low cost entry-level HF signal generator to determine if it would improve the original WR-50C's rather limited attenuation control.

The resulting performance is shown in Table 2.

Frequency (MHz)	Output Level into 50 ohms		Attenuator Range (dB)
	Max (dBm)	Min (dBm)	
1	-17	-85	68
3	-12.5	-80	67.5
5	-17.5	-85	67.5
10	-15	-83	68
20	-18	-81	63
30	-18	-74	56
40	-21	-75	54

Table 2 : The maximum output level of the modified Wiz WR-50C entry level signal generator was similar to the unmodified generator but the attenuator range was significantly improved.

So, yes, it does significantly improve the signal generator's performance. You can see this more clearly in Figure 13. The new attenuator, rough though it was, gave an attenuation range of more than 60dB up to about 25MHz, and well over 50dB of adjustment range from 30 to 40MHz. The range was limited by the basic construction method used, the modest equipment isolation, and imperfect matching to the internal WR-550C circuit prior to the attenuator. Better results could be achieved with more shielding in the signal generator, better matching, and closer attention to good RF grounding practice.

Nonetheless, the new front panel RF output level control was a pleasure to use, and gave a useful improvement over the original manufacturer's design. I felt this was a satisfactory outcome for such a basic prototype.

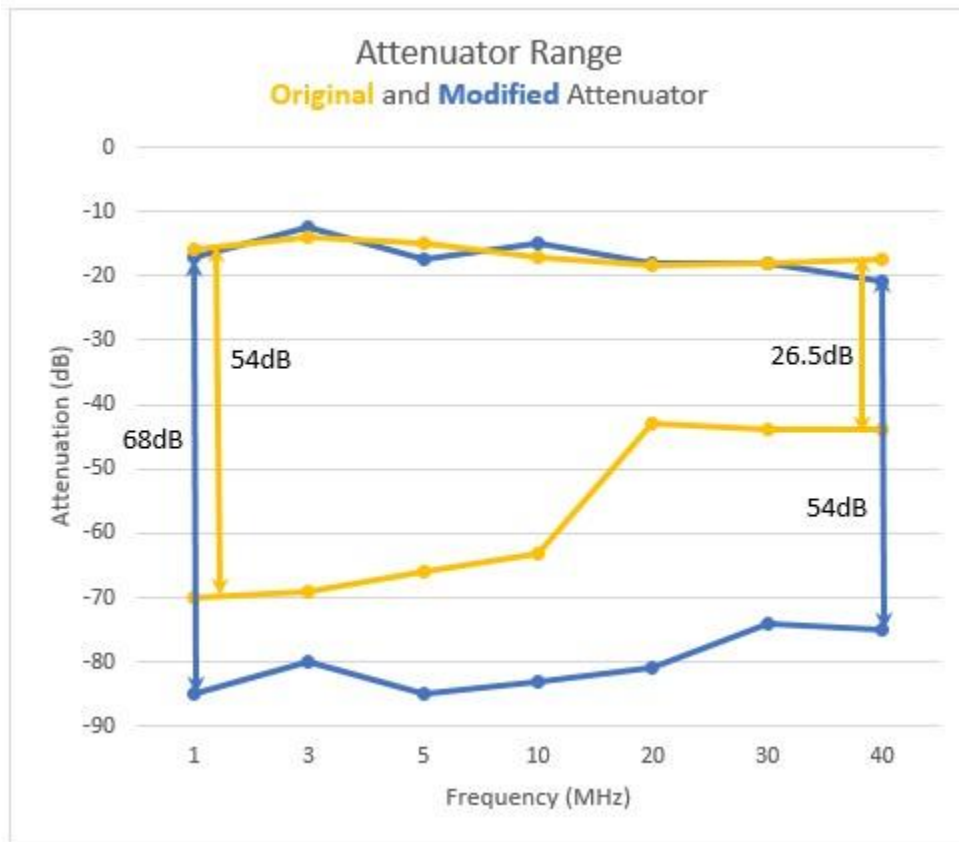


Figure 13 : The improvement over the original attenuator design is clearly visible here with up to 30dB attenuator range improvement across the signal generator's range from 1 to 40MHz.

Note: Output from the signal generator below 500kHz is significantly reduced with this modification due to the dimensioning of transformers T1 and T2. These require more turns to permit use down to 85kHz but this would likely compromise performance above 50MHz. I have little use for an RF generator at frequencies below 100kHz but if time permits, I may try other arrangements of T1 and T2 to see if I can get useful performance down to, say, 250kHz.

## Improvements to the Variable RF Attenuator

Based on the initial results with this version, I decided to redesign the PCB layout to suit SMD components. Not only would this version be more compact, but I expected an improvement in the performance of the variable attenuator, particularly over the 200 – 300MHz range.

The SMD PCB layout is shown below.

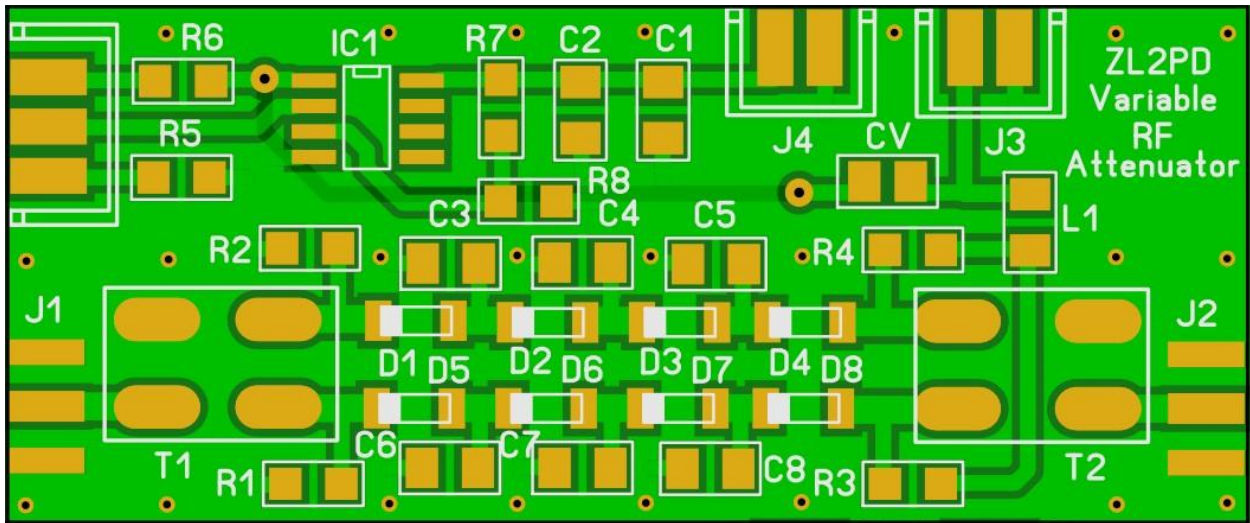


Figure 14 : The SMD version was developed to see if this would give improved attenuator performance. It has a 'CV' jumper on the board to allow easier modification for use with a possible future external microcontroller and digital display.

- J1 and J2 are designed for edge-mounted SMA connectors.
- J3 is for use with an external control voltage from, say, an external microcontroller. In that case, jumper "CV" should be left OPEN. In normal use, control is via the circuit around IC1 and the 10k linear potentiometer wired to the three pads at the upper left hand edge of the PCB. In this case, jumper "CV" should be linked with a blob of solder.
- J4 is for the external +12V power supply (25mA max).

## Construction

I'm no expert on SMD construction, and lacking an SMD reflow oven and other suitable SMD tools, this board was built by hand. That's why it's a little "rustic" in appearance.

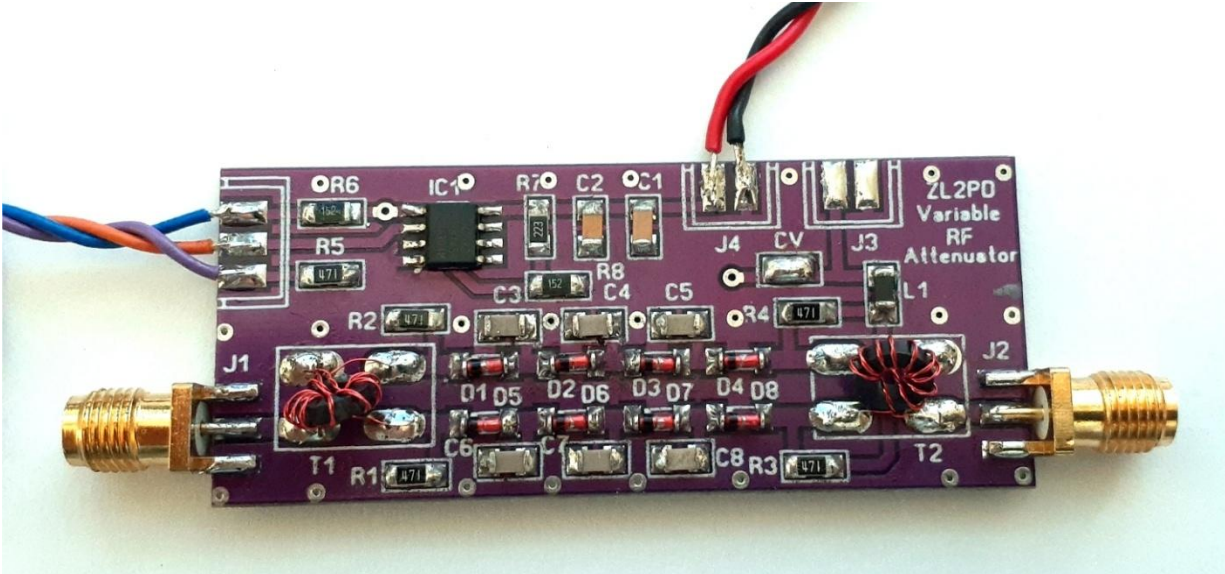


Figure 15 : The completed prototype SMD variable attenuator measures 60 x 25 x 8mm (w/o connectors) and 80 x 33 x 8mm (with connectors fitted).

Despite the use of tiny SMD parts, it's relatively easy to build. It's designed for the larger 1206 parts because my eyesight is not up to using the smaller 0805-series parts. The toroids are wound by hand and soldered to the pads. This arrangement reduced the height of the assembled unit slightly and eased later mounting arrangements.

I did not bother selecting diodes with closely matching characteristics. I suspect that by using a series of eight SMD diodes in sequence from an SMD tape, they are very likely to be of similar performance. As far as I can tell, that's proven to be the case. Or, probably, matching doesn't matter too much in this circuit.

Transformers T1 and T2 are wound on a pair of small FT23-43 toroids. I used 38SWG enameled copper (EC) wire. Cut 200mm of wire and fold in half. That gives you a pair of wires 100m long. Twist this pair using a drill to get about 2-3 twists per cm. It's not critical but I found it easier to wind the toroid with the twisted wire.

Wind ten turns of this 'bifilar' wire onto the toroid. Repeat the process for the second transformer.

The enamel on modern EC wire can be removed with just the heat of a soldering iron when you 'tin' the ends of the prepared wire prior to mounting on the PCB. Tin about 5mm of each end.

I could have used cheaper Chinese made toroids instead of the suggested Amidon FT23-43 parts but the wide variation I have found in the characteristics of Chinese made toroids, based on my measurements of a few hundred of them to date, makes it tough to recommend them. It may be worth trying them if you need to save a few dollars or if you have them to hand.

## SMD Variable Attenuator Parts List

Component	Value	Notes	Quantity
R1 – R5	470R	1206 SMD resistor	5
R6, R8	1k5		2
R7	22k		1
VR1	10k linear potentiometer		1
C1	10n	1206 SMD ceramic capacitor	1
C2	100n		1
C3 – C8	4p7		6
L1	1uH	1206 SMD	1
T1, T2	FT23-43 toroid	Amidon etc	2
D1 – D8	1N4148	1206 SMD	8
IC1	LM358	SOT-8 package	1
J1, J2	SMA female PCB edge mount		2
J3, J4	2 pin Dupont male (Optional)	See note	2
J5	3 pin Dupont male (Optional)		1
	Note: If J3-5 are fitted, matching female Dupont 0.1" connectors will also be required		
Wire	38SWG enamelled copper wire		400mm
Wire	Hookup wire	As required for VR1, DC etc	
Knob	For VR1		User selected
PCB	--		1

Table 3 : Parts list for the SMD attenuator

Based on the parts and PCB prices I paid (in January 2022), the estimated build cost is likely to be less than \$US10 per attenuator.

## Measured Results

I was very pleased to find that the anticipated performance improvements were achieved with the revised SMD layout.

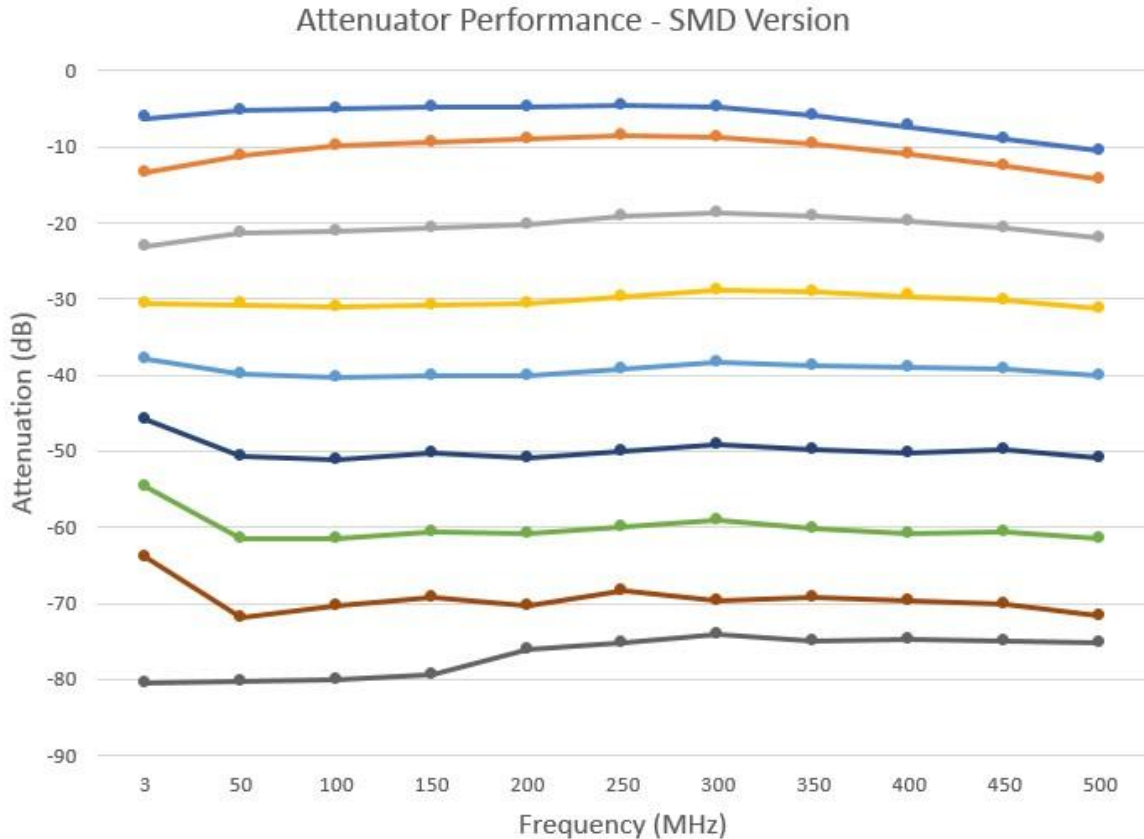


Figure 16 : The frequency response of the SMD version of the attenuator was measured into a 50 ohm termination from 3 to 500MHz by setting potentiometer VR1 in approximately 10dB increments (at 200MHz) and at minimum to maximum attenuation settings.

The variable attenuator's performance is almost ideal up to 300MHz, and provides up to 70dB of attenuation, with care, for applications from 3MHz to 500MHz. A reduced attenuation range, from about 10 to 60dB, is achieved up to 1GHz.

A proviso – These measurements were made in a 50 ohm environment. The input and output impedance of the attenuator is actually likely to be somewhat different. It's performance may therefore vary if your test setup varies from a 50 ohm source and load match.

That said, for a set of low cost readily available components, I think the result achieved here represents a very satisfactory and useful outcome.

## Concluding Comments

Clearly, this work is built on the shoulders of some of the giants of the industry from back in 1973. My thanks to the team at HP Colorado for the basic design idea that I've turned into this interesting and useful variable RF attenuator.

This device has already proven to be useful around here, and I may develop a digital version in the near future depending on my requirements and user interest.

## Downloads:

- ▶ [PCB Layout: Thru-hole component version Gerber PCB files](#) (This ZIP file also contains a JPG image for etching a single sided test UNDRILLED thruhole PCB as I used in the initial tests described above)
- ▶ [PCB Layout: SMD component version Gerber PCB files](#)

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