Broadband, Low-Loss 5- and 6-Bit Digital Attenuators

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ABSTRACT

Low-loss 5- and 6-bit MMIC digital attenuators covering DC-16 GHz have been designed, fabricated and tested. These attenuators provide exceptional performance, with reference state insertion loss of less than 5 dB at 16 GHz (for the 6-bit chip) and 28 dB of dynamic range of attenuation. The input and output VSWRs of the attenuators are better than 1.6:1 over all attenuation states and frequencies. These digital attenuators have an input third order intercept point of 37 dBm.

INTRODUCTION

Digital step attenuators offer precise, well-controlled attenuation ranges over frequency while maintaining high power handling and good thermal stability. The conventional approach to digital attenuator design relies on a series of switched-path, binary weighted "Tee" or "Pi" attenuators connected by SPDT switches. This approach exhibits high reference state insertion loss due to the cumulative loss of all the SPDT switches for a multi-bit attenuator design, thus requiring additional gain stages and occupying a large chip area in the system. Recently published results in MMIC digital attenuators overcame this problem by combining switching and attenuation functions in the same structure. Khabbaz et al [1] described a 4-bit attenuator using a distributed topology with switches. No results were given regarding the VSWR performance of this attenuator with frequency and attenuation states. Ali et al [2,3] demonstrated a compact 4-bit attenuator using a single "Double-PI" circuit having single and dual-gate FETs with DC-6 GHz performance. McGrath and Pratt [4] realized a DC-12 GHz 4-bit attenuator using a "Bridged-Tee" configuration for higher bits (4 dB and 8 dB) and switchable "Tee" for lower bits.

This paper describes the design and performance of 5- and 6-bit digital attenuators using a modified "PI" type embedded switched-attenuator circuit topology [5].

MMIC DIGITAL ATTENUATORS

The attenuators use MESFET switches with 0.5μm gates on MBE epitaxial material. These switches use a single recess through a thick N^+ layer to achieve optimal switch performance. The measured on-resistance is 1.8 ohm-mm and C_{off} is .275 pf/mm for a resulting cutoff frequency of 320 GHz. The typical pinchoff and breakdown voltages for the switch process are 2V and 10V, respectively.

The device uses two types of resistors, both a Ni-Chrome resistor (with 10 ohms/square) and an epitaxial resistor (at 500 ohms/square). Capacitors are 2500Å thick Si_3N_4. The control voltages used for the MESFET switches are 0.0 and -5.5 volts. Photographs of the fabricated 5- and 6-bit attenuators are shown in Figures 1a and 1b. The 5- and 6-bit devices were designed to be

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the same size and pinout, both measuring 116 x 92.5 x 6 mils.

The 5-bit digital attenuator is comprised of 0.5, 1, 2, 4 and 8 dB bits, resulting in 15.5 dB of dynamic range of attenuation. Two 4 dB bits were cascaded to achieve the 8 dB bit in order to achieve broader bandwidth. The 6-bit digital attenuator has 0.5, 1, 2, 4, 8 and 8 dB bits providing 23.5 dB of dynamic range of attenuation. The basic schematic of a higher bit is shown in Figure 2. Each bit uses two series switches (in parallel) and two shunt switches. The two series switches are actually a single switch configured so as to reduce line length parasitics which become critical at the higher frequencies. In the reference state the series switches are "on" and the shunt switches are "off," providing minimal insertion loss. Conversely, in the high attenuation state, the series switches are "off" leaving a series resistor, and the shunt switches are "on," forming a pi-network resistive attenuator. In the 1 and 2 dB bits an additional capacitor is added across the series "pi" resistor to adjust the flatness of the attenuation with frequency.

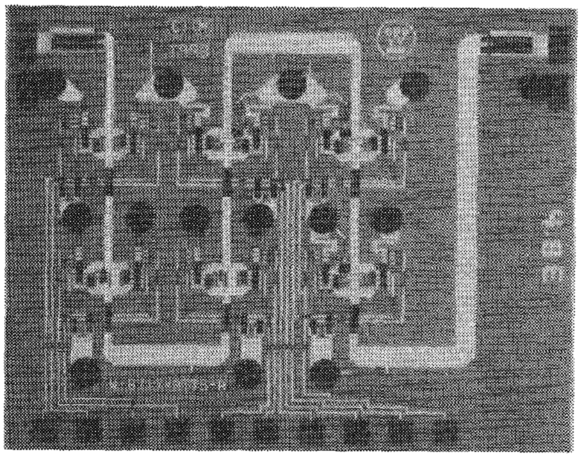

Figure 1a. Photograph of the 5-bit MMIC digital attenuator.

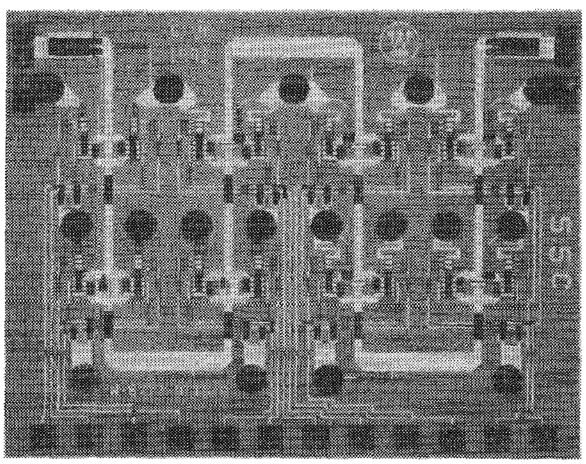

Figure 1b. Photograph of the 6-bit MMIC digital attenuator.

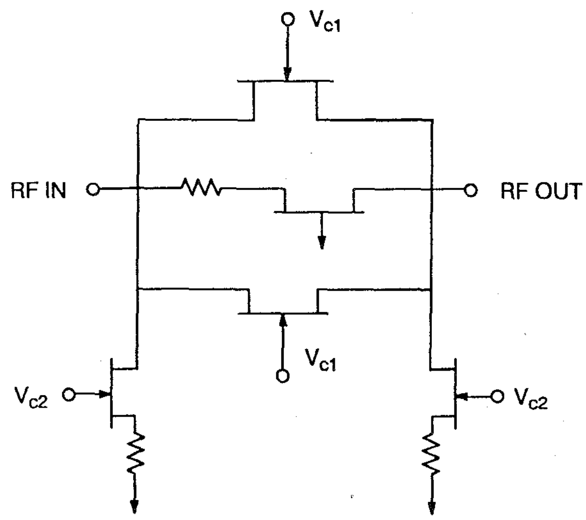

Figure 2. Rf schematic of the 4 dB bit.

MEASURED PERFORMANCE

Rf probed insertion-loss and attenuation performance of the 6-bit attenuator are shown in Figure 3. The insertion loss is less than 5 dB from 2 to 16 GHz for this device, and if the input/output blocking caps are shorted, this extends down to DC. The total relative attenuation is greater than 22.5 dB across the band. The input and output VSWRs for the multiple bit states are shown in Figures 4 and 5. Although not all bit states are shown in these figures, the device has better than a 1.6:1 VSWR over all attenuation states from DC to 16 GHz, both at the input and output. The devices have an input third order intercept point of 37 dBm, and the bias current is typically less than 150μA for any given attenuation state. The associated phase shift of the device was linearly increasing with frequency and had 35 degrees of phase shift at 10 GHz at the highest attenuation state.

Further fixture measurements were also performed on the 5-bit attenuator to demonstrate the low frequency performance of the device. In these measurements, the input/output blocking capacitors were intentionally shorted to extend the frequency response down to DC. Figures 6, 7 and 8 are direct screen plots from an HP8510

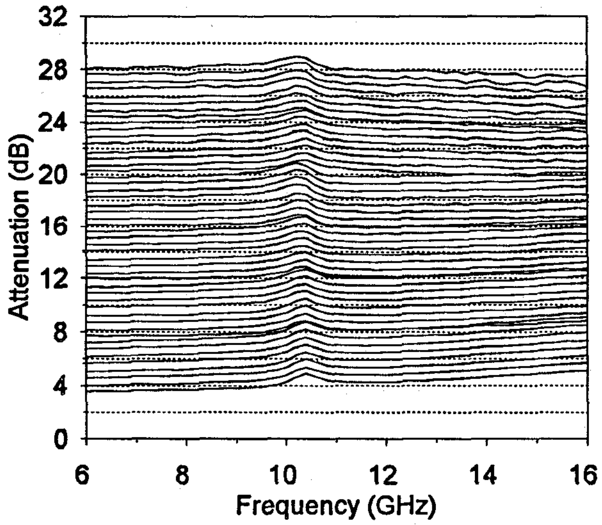

Figure 3. Rf probe measured attenuation for the 6-bit digital attenuator.

network analyzer, and show the measured attenuation and input/output return losses, respectively, for a typical 5-bit attenuator. No fixture losses were subtracted from the measurement, and they are estimated to be about 0.4 dB at 10 GHz. Inspection of the measured curves show that the relative attenuation stays very uniform down to 100 MHz, and the return

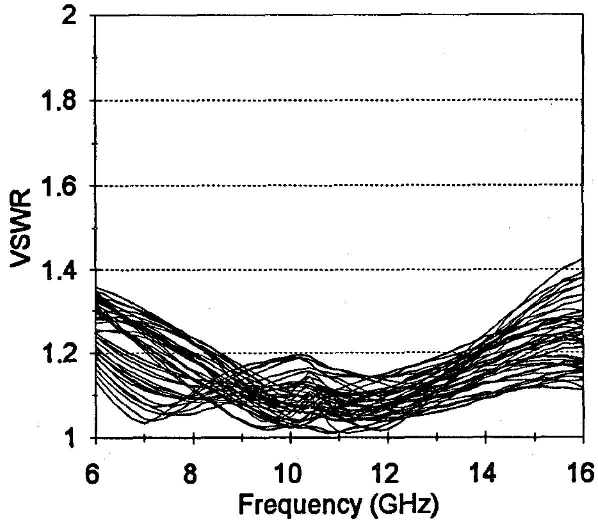

Figure 4. Rf probe measured input VSWR for all states of the 6-bit digital attenuator.

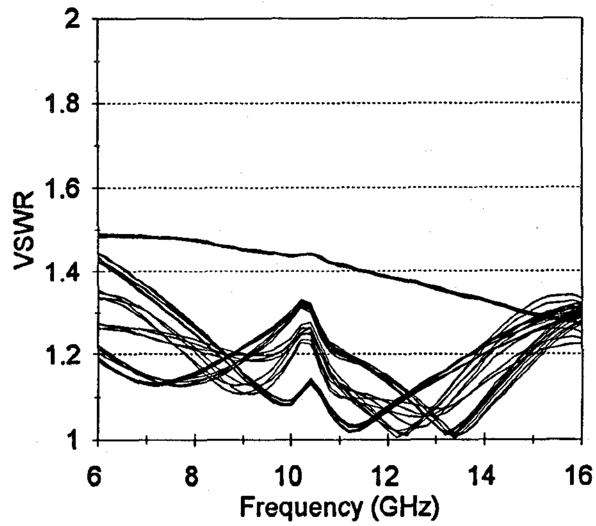

Figure 5. Rf probe measured output VSWR for all states of the 6-bit digital attenuator.

loss is better than 16 dB (1.4:1 VSWR) over all attenuation states on input and output.

CONCLUSION

The digital attenuator design presented here has good performance characteristics over an extremely wide bandwidth (DC to 16 GHz). While other designs have had comparable insertion loss, this design is also shown to have very good input/output VSWRs (1.5:1) in all states. These attenuators can be used in many military and commercial system applications due to their broad bandwidth and small size.

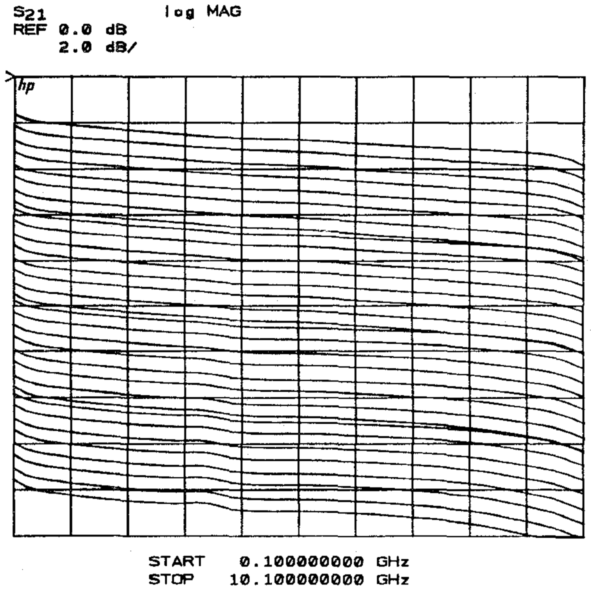

Figure 6. Fixture measurement of attenuation for 5-bit attenuator.

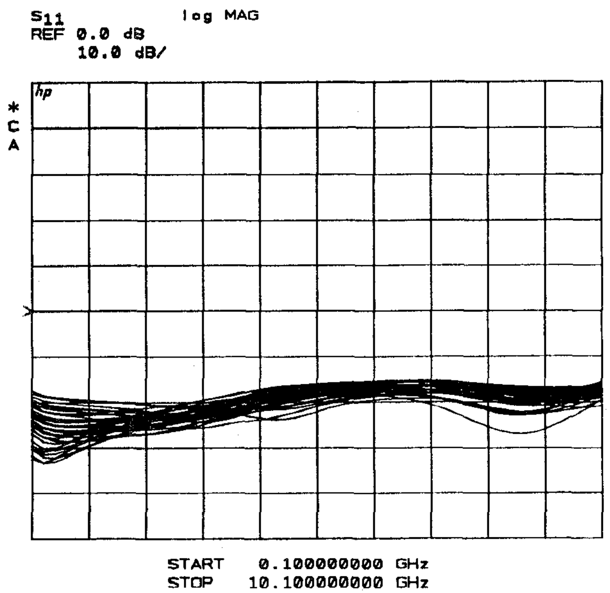

Figure 7. Fixture measurement of input return loss for 5-bit attenuator.

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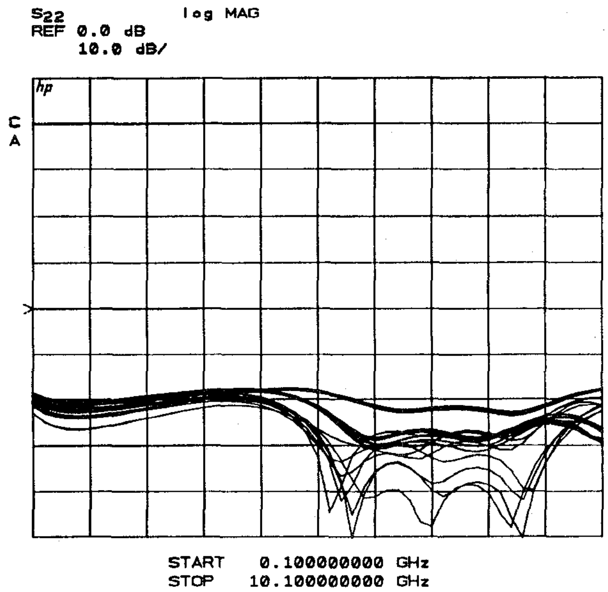

Figure 8. Fixture measurement of output return loss for 5-bit attenuator.

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