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A TEMPERATURE-COMPENSATED LINEARIZING TECHNIQUE FOR MMIC ATTENUATORS UTILIZING GaAs MESFETS AS VOLTAGE-VARIABLE RESISTORS

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ABSTRACT

A unique linearizing technique for MMIC attenuators utilizing GaAs MESFETs as voltage-variable resistors and an off-chip control circuit is reported. This technique produces an attenuation vs. control voltage characteristic that is linear (in dB) and inherently temperature compensated.

INTRODUCTION

Variable attenuators are among the most versatile and widely used signal processing components available today. They are used extensively in applications such as Automatic Gain Control (AGC) and temperature-compensation circuits to control gain and power. In recent years, the advances in MMIC technology has spawned new interest in GaAs MESFET attenuators because they offer several distinct advantages over balanced PIN diode attenuators. For instance, multioctave performance is obtainable due to the absence of couplers and operation down to dc is straightforward. Unfortunately, most attenuators have a nonlinear log (attenuation) vs. control voltage characteristic that complicates the design of control circuitry. An attenuator with linear behavior that is stable over temperature is a valuable component that greatly simplifies amplifier and subsystem-level design. In addition, it opens numerous new applications such as modulators and phase shifters. The work described here successfully demonstrates a linear attenuation vs. control voltage curve that is inherently temperature compensated and covers the dc - 20 GHz frequency band. The attenuator can be used discretely or in combination with other MMIC functions to produce MMICs with higher levels of functional integration.

FET ATTENUATOR CHARACTERISTICS

A standard pi-pad topology was chosen to implement the attenuator (see Figure 1). In this configuration, attenuation is primarily set by the impedance of the series FET while the impedance of the shunt FETs are optimized to maintain a good 50Ω impedance match. Generating the appropriate series and shunt gate voltages (V_{Series} and V_{Shunt}) to achieve these impedances is a difficult task. Several programmable approaches have been used where the attenuation level is measured and the corresponding gate voltages are recorded. However, the nonlinear relationship of channel resistance to gate voltage and its strong temperature dependence make such a programmable approach difficult to implement consistently. A real-time feedback loop is thus required.

This feedback loop is possible because the dc and rf FET resistances are, for practical purposes, about equal. This is perhaps the most significant advantage that the GaAs MESFET approach offers over PIN diodes. It allows a control circuit operating at dc to generate the appropriate gate voltages to control the rf attenuation and impedance match. The control circuit design incorporates separate on-chip reference devices operating at dc, along with the rf attenuator.

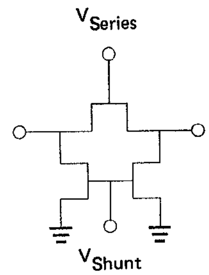

Figure 1. PI Pad Attenuator

IMPEDANCE MATCHING CIRCUIT

The impedance match was achieved using a technique previously reported by Barta, et al. (see Figure 2) [1]. The attenuator chip contains two identical pi-pad attenuators, one for attenuating the rf signal, and the other to establish V_{Shunt}. A voltage divider sets a constant voltage corresponding to a 50Ω load at the noninverting input to the Operational Amplifier. Any change in resistance of the series FET changes the voltage at the inverting input of the Operational Amplifier. The Operational Amplifier acts to adjust the resistance of the shunt FETs, thus maintaining a 50Ω impedance match.

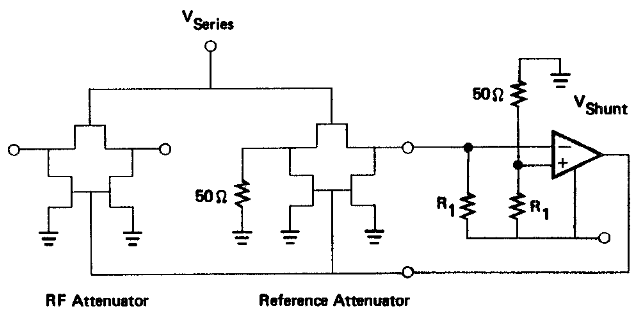

Figure 2. Impedance Matching Circuit

Although the Operational Amplifier control circuit provides an excellent match, the log (attenuation) vs. series gate voltage

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curve is highly nonlinear (see Figure 3). Such a circuit is extremely difficult to use because small variations in V_{Series}, at high attenuation levels, result in large attenuation changes. Controlling the attenuation level is further complicated by the temperature dependance of the FET channel resistance (see Figures 3 and 4).

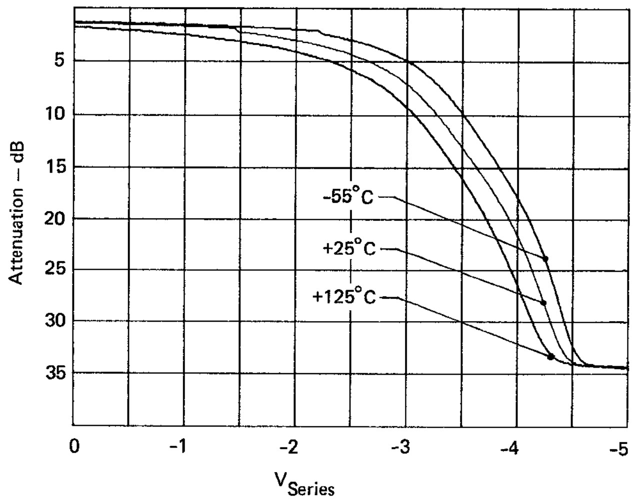

Figure 3. Attenuation vs. Series FET Gate Voltage using Impedance Matching Circuit of Figure 2

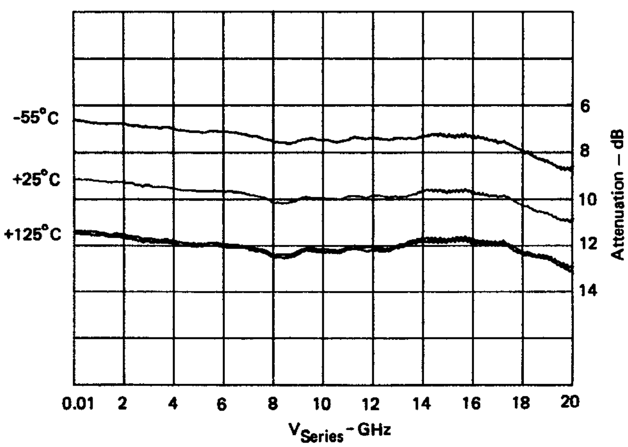

Figure 4. Attenuation vs. Frequency over Temperature for a Fixed V_{Series}

LINEARIZING CIRCUIT

A control circuit was developed to compensate for the nonlinear relationship of channel resistance to gate voltage. The linearizing circuit places a FET that is identical to the series FET of the rf attenuator in a feedback loop (see Figure 5). The FET is combined with a constant-current source to produce a voltage drop proportional to the low field channel resistance. That voltage is fed back to the inverting input of the Operational Amplifier (V-) where it is compared to the input control voltage ($V_{Control}$). Since the Operational Amplifier is used as a differential amplifier, the output of the Operational Amplifier adjusts V_{Series} such that the voltage drop across the reference FET is changed to maintain a virtual null between the noninverting and inverting inputs. It can be seen from equation (1) that the relationship between control voltage and series resistance, rather than gate voltage, is now linear.

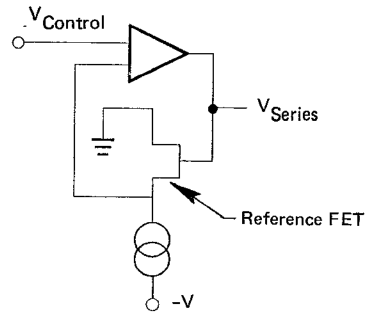

Figure 5. Basic Linearizing Circuit

$$V_{Control} = V+ = V- = -(I_{Reference})(R_{Series}) \quad (1)$$

Thus for any incremental delta in $V_{Control}$, an incremental change occurs in R_{Series} because $I_{Reference}$ is constant. The result is an attenuation curve that is nearly linear, in dB, with control voltage (see Figure 6).

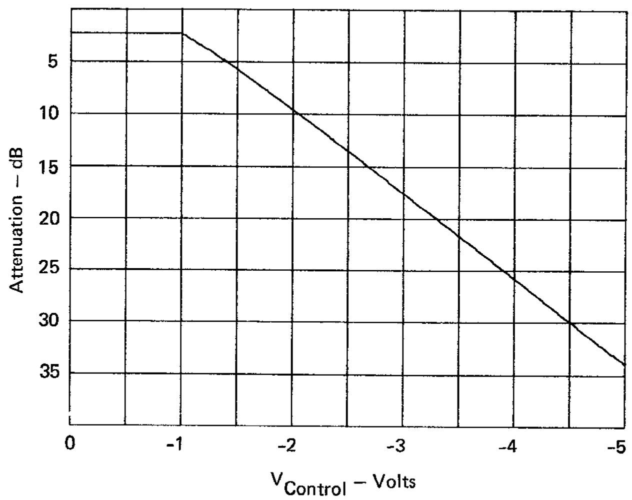

Figure 6. Attenuation vs. Control Voltage for Linearizing Circuit (F = 2 GHz)

The power of this linearizing technique is demonstrated in the temperature performance. Although the FET channel resistance is a strong function of temperature, the Operational Amplifier dynamically adjusts V_{Series} of the reference FET to compensate for temperature effects (see Figure 7a). It can be seen that no significant changes in the slope of the attenuation vs. control voltage curve (likewise the attenuation for a given $V_{Control}$) occur over the -55^{o}C to +125^{o}C temperature range. In Figure 7b, the attenuation level changes by less then 0.4 dB over the -55^{o}C to +125^{o}C temperature range. This is extremely valuable in the design of temperature compensation circuits and circuits requiring high degrees of accuracy.

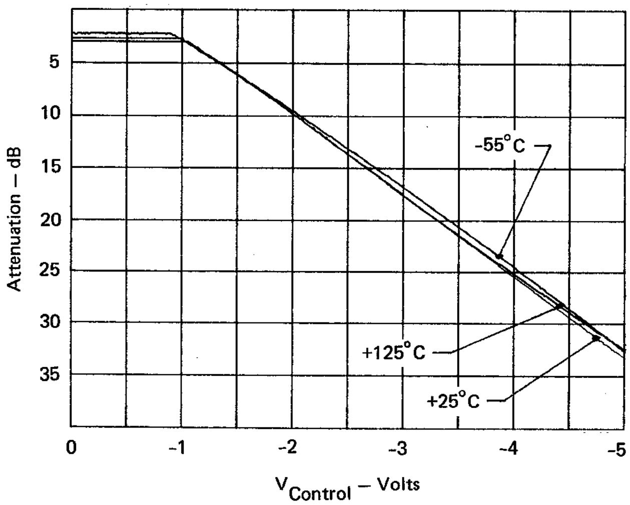

Figure 7a. Attenuation vs. Control Voltage over Temperature

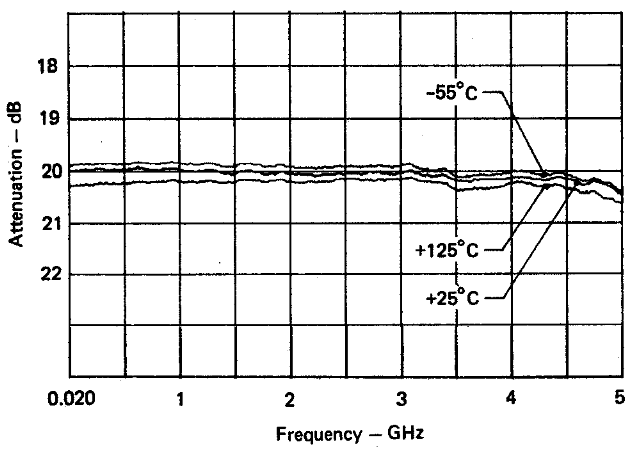

Figure 7b. Temperature Performance of Attenuation at Fixed $V_{Control}$

Another beneficial feature of this linearizing technique is circuit flexibility. The slope of the attenuation vs. control voltage curve is easily controlled by changing the reference current through the reference FET. This allows greater flexibility in adjusting slope for different applications. The linearizing control circuit of Figure 5 also forms the basic building block for more complicated Operational Amplifier control circuits. For example, a temperature transducer can be added for temperature compensation applications.

ATTENUATOR CHIP AND PERFORMANCE

An attenuator chip has been designed and fabricated that incorporates the rf pi-pad attenuator, a dc equivalent pi-pad reference attenuator for impedance matching, and a dc equivalent reference FET for linearization. The monolithic attenuator chip measures 500 microns by 850 microns (see Figure 8).

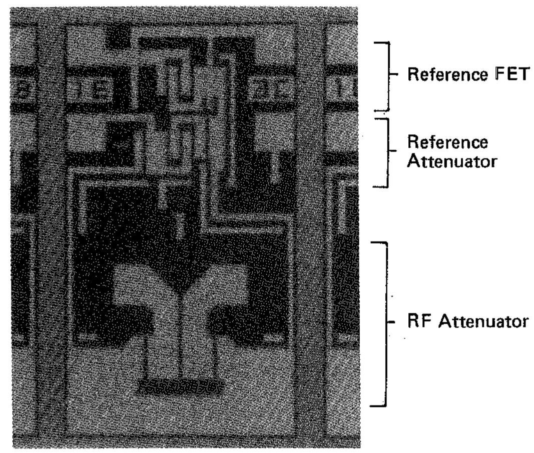

Figure 8. Attenuator MMIC

The small size and layout of the chip have significantly reduced additional parasitic elements to yield excellent broadband performance (see Figure 9). The Minimum Insertion Loss (MIL) is less than 1.7 dB at 10 GHz, and 2.1 dB at 20 GHz. The attenuation range is 13 dB with less than 1 dB change in flatness from dc to 20 GHz. Over a more limited bandwidth, the attenuation range improves and is better than 25 dB from dc to 2 GHz.

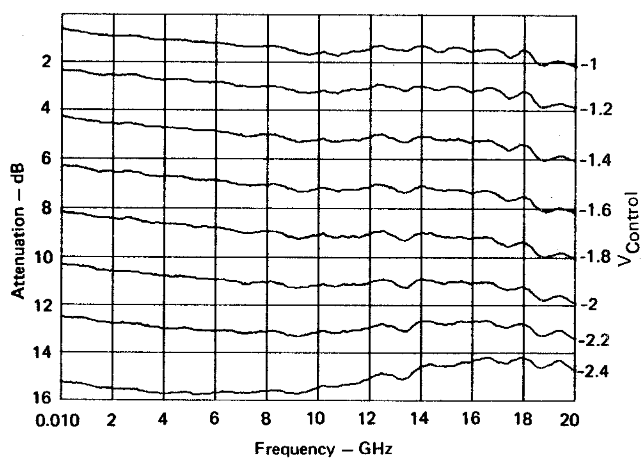

Figure 9. Attenuation Levels at Multiple Control Voltages

The combination of FET attenuator and linearization technique produces a very broadband circuit. Because the control circuit works at dc and is intrinsically decoupled from the rf, the slope of the attenuation vs. control voltage curve is independent of frequency (see Figure 10). Note that the chip and control circuit were mounted in a TO-8 header for measurement simplicity, thus limiting the bandwidth to 5 GHz.

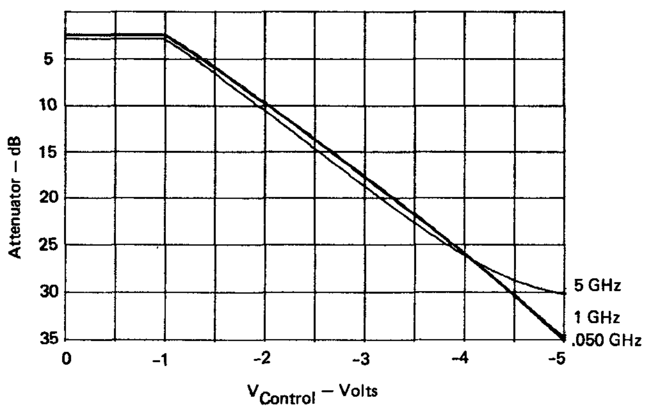

Figure 10. Attenuation vs. Control Voltage for Multiple Frequencies

In addition, the attenuator is designed such that multiple chips may be cascaded for applications requiring higher dynamic ranges without duplicating the off-chip Operational Amplifier control circuit.

FUTURE WORK

Perhaps the biggest challenge in the development of GaAs FET attenuators is the rf power handling issue. These devices work well for small signal (typically less than +10 dBm input power). However, they experience premature saturation, attenuation expansion, and transient effects when driven with powers greater then +10 dBm. This unfortunately limits their applications in many systems.

Increasing power handling involves extending the linear region of the dc I-V curve. This can be achieved by altering the channel doping and increasing gate length. Both of these techniques are in development and are the focus of future work.

CONCLUSION

A linearizing technique has been demonstrated that solves many of the problems associated with GaAs FET variable attenuators. The technique generates a linear attenuation vs. control voltage curve that is stable over the -55°C to +125°C temperature range and is broadband covering the dc to 20 GHz frequency band. In addition, the attenuator is compatible with FET amplifier design for MMIC integration to achieve higher levels of functional integration.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

1. Gary S. Barta, et al, "A 2 to 8 GHz Levelling Loop Using a GaAs MMIC Active Splitter and Attenuator," 1986 IEEE Microwave & Millimeter-Wave Circuits Symposium Digest of Papers, pp. 75 - 79.