Wideband 5-bit MMIC Digital Attenuator With High Precision

Chengpeng Liu, Wei Zou and Guoqiang Wang
Sichuan Institute of Solid State Circuits, China Electronics Technology Group Corp., Chongqing, P. R. China

Abstract—This paper mainly introduces the Wideband 5-bit MMIC digital attenuator with high precision. Firstly, the theories of basic GaAs digital attenuator MMIC’s configurations are searched. Secondly, every possible configuration is contrasted, subsequently, appropriate topology is selected for each stage. This attenuator has been realized by 0.5 μm GaAs pHEMT process. Simulation results of the digital attenuator have 0.25dB resolution and 7.75dB dynamic attenuation range, Input Voltage Standing Wave Ratio(VSWR_{IN}) was less than 1.55 and Output Voltage Standing Wave Ratio(VSWR_{OUT}) was less than 1.6 for all attenuation states, high attenuation accuracy is less than ±0.26dB; insertion loss is less than 1.3dB; The layout of the digital attenuator with a chip size is 0.93 mm×1.45 mm

Index Terms—wideband, 5-bit, digital attenuator, high precision

I. INTRODUCTION

MMIC variable attenuators are required in many microwave systems for automatic gain control for receiver and transmitter systems, amplitude weighting for phased array radars and temperature compensation of microwave amplifiers. An attenuator specially is a key device of the module used in BFN because the attenuator is to control of the amplitude[1~4].

The attenuator has two types of control method, analog attenuator and digital attenuator. Digital attenuators offer better linearity, high power handling, and easy and accurate control of attenuation, So MMIC digital attenuators have gained lots of interest in recent years[5~6].

The requirements of the MMIC digital attenuators to be designed are as following: small size, high attenuation accuracy, low insertion phase shift, high reliability and low cost[7].

In this paper, we describes an Wideband 5-bit MMIC digital attenuator with high precision. The digital attenuator has obtained excellent performances and implements in 0.5um GaAs pHEMT MMIC.

II. CIRCUIT DESIGN

Published literature on MMIC digital attenuators mainly rely on three basic types of topologies: i) Tee attenuator; ii) Bridged-Tee attenuator; iii) Pi attenuator. All of them relay on a signal through either a bypass line or an attenuation cell with RF switches. Fig.1, Fig.2 and Fig.3 show the topologies of Tee attenuator, Bridged-Tee attenuator and Pi attenuator[8~11].

Figure 1. Tee attenuator

Figure 2. Bridged-Tee attenuator

Figure 3. Pi attenuator

Figure 4. The equivalent circuit of Bridged-Tee attenuator

http://dx.doi.org/10.3991/ijes.v1i2.3258
WIDEBAND 5-BIT MMIC DIGITAL ATTENUATOR WITH HIGH PRECISION

Figure 5. Mainly schematic of the digital attenuator

Referring to FIG.5, the schematic of the x-band MMIC digital attenuator with low phase shift is shown. To achieve good performance, the circuit configuration as well as the process conditions, should be selected properly.

The digital attenuator consists of switched pHEMTs, resistors, and microstrip lines. The switched pHEMTs in the circuit are controlled through 8kΩ resistors of the gate poles, which provide enough radio frequency isolation between the gate of each switched pHEMT and the control sources. And the low value resistors are used to form the topologies for attenuators.[12-14]

The five required attenuation bits are 0.25dB, 0.5dB, 1dB, 2dB and 4dB, providing a dynamic range from 0.25dB to 7.75dB. The most attenuation of five main attenuation states is 4dB. Bridged-Tee attenuator are used for the Wideband 5-bit MMIC digital attenuator. Bridged-Tee attenuator (Fig.2) has good performance in insertion loss, VSWRIN and VSWROUT also has better performance than Pi attenuator.[15-17]

Referring to FIG.4, The equivalent circuit of Bridged-Tee attenuator shows (R2=R3):

$$Z = \left[ \begin{array}{c} Z_{11} \\ Z_{21} \\ Z_{12} \\ Z_{22} \\ Z_{in} \\ Z_{out} \end{array} \right] = \left[ \begin{array}{c} R_{1}Z_{0} + R_{i} \frac{Z_{0}^{2}}{R_{1} + 2Z_{0}} + R_{i} \\ Z_{0}^{2} + R_{i} \frac{R_{0}Z_{0} + Z_{0}^{2}}{R_{1} + 2Z_{0}} + R_{i} \\ \sqrt{Z_{in}} \cdot \sqrt{Z_{out}} \end{array} \right]$$

The characteristic impedance of transfers lines connect to port1 and port2 are $Z_{in}$ and $Z_{out}$, so:

$$Z = \left[ \begin{array}{c} Z_{11} \\ Z_{21} \\ Z_{12} \\ Z_{22} \end{array} \right]$$

The S-parameters are:

$$S_{11} = \frac{Z_{11} + Z_{in} - Z_{22}}{Z_{11} + Z_{in} + Z_{22}}$$

$$S_{22} = \frac{Z_{22} - Z_{11} - Z_{in}}{Z_{22} + Z_{in} + Z_{11}}$$

$$S_{21} = \frac{2Z_{21}}{Z_{11} + Z_{in} + Z_{22}}$$

$$S_{12} = \frac{2Z_{12}}{Z_{11} + Z_{in} + Z_{22}}$$

And:

$$L = 20 \log_{10} |S_{21}|$$

$$10 \log_{10} |S_{11}| = -\infty$$

From (1)-(8), the value of $R_{1}$ and $R_{4}$ in Bridged-Tee attenuator can show below:

$$R_{1} = Z_{0} \left( \frac{Z_{in}}{Z_{out}} - 1 \right)$$

$$R_{4} = \frac{Z_{0}}{10^{20} - 1}$$

From (9)-(10), the value of $R_{1}$ and $R_{4}$ can be calculated by given attenuation bits.

The digital attenuator integrated driver was realized by enhancement / depletion (E/D) technology on GaAs substrate. The digital portion adopts a direct coupled FET logic (DCFL) structure, which had the advantages of simple structure, high speed, low power consumption, simplify the system application and enhances the system reliability. The digital attenuator has built-in 5 voltage control port transistor-transistor logic (TTL) driving circuit to feed the pHEMTs’ gate poles. In this case, when the control voltages are set at 0V, which is the negative pinch-off voltage of switched pHEMT, the switched pHEMT will work at its “off” state (high resistance). When the control voltages are set at 5V, The switched pHEMT will work at its “on” state. So the required attenuation can be obtained by switching the control voltages at the port.

The digital attenuator is at the minimum attenuation state, when all of the five control voltages are 5V. In this case, the attenuator has a minimum insertion loss. The attenuator is at the maximum attenuation state, when all of the five control voltages are 0V.

The above description is equally available for the other states. The control signal with the value of 0V is taken as “0” and the control signal with the value of 5V is taken as “1.” The truth table of the digitally-controlled main attenuation states shows in Table 1, which is referred to in FIG. 6.
TABLE I. TRUTH TABLE OF MAIN ATTENUATION STATES SHOWS ("1" AS 0V, "0" AS -5V)

|        | 0.25dB | 0.5dB | 1dB   | 2dB   | 4dB   |
|--------|--------|-------|-------|-------|-------|
| MIN    | 1      | 1     | 1     | 1     | 1     |
| 0.25dB | 0      | 1     | 1     | 1     | 1     |
| 0.5 dB | 1      | 0     | 1     | 1     | 1     |
| 1 dB   | 1      | 1     | 0     | 1     | 1     |
| 2 dB   | 1      | 1     | 1     | 0     | 1     |
| 4 dB   | 1      | 1     | 1     | 1     | 0     |
| MAX    | 1      | 1     | 1     | 1     | 1     |

The layout of the Wideband 5-bit MMIC digital attenuator with high precision as shown in Fig.6. RF input and output are at the either end with complementary pairs of the control lines along one edge, control lines the other edge are all connect to GND. The layout of the digital attenuator with a chip size is 0.93 mm × 1.45 mm.

III. SIMULATED RESULTS

Using the new configuration, a digital attenuator has been realized by 0.5um GaAs E/D process. The simulation of our digital attenuator have been presented based on the ADS2008. Broadband and high precision performance was achieved by optimization of the transmission line parameters and the resistor values. The Monte Carlo analysis were also utilized in the attenuator design, the results predicted that the design has stability against the process variations.

The insertion loss is shown in Fig.7. The attenuator achieved a minimum insertion loss of 0.5~1.3dB in the entire DC~4GHz band. Referring to Fig.8, It can be seen that each curve in the figure represents a different attenuation setting in a roughly 0.25dB step with over 7.75dB dynamic range, for which a proper combination of the control voltages was chosen. Fig.9 and Fig.10 show VSWRIN and VSWROUT for 35 attenuation states. The VSWRIN was always less than 1.55 and the VSWROUT was always less than 1.6 at any attenuation setting, the attenuation accuracy is less than ±0.26dB;

Figure 6. The layout of Wideband 5-bit MMIC digital attenuator with high precision
IV. CONCLUSION

The theory, design, and measurement of the Wideband 5-bit MMIC digital attenuator with high precision are presented. Appropriate topology is selected for stages. To ensure high yield, performance redundancy optimization strategy is used in design. The simulation results of the developed MMIC chips show that the 5-bit MMIC digital attenuator has 0.25dB resolution and 7.75 dB dynamic range, attenuation range, VSWR IN was less than 1.55 and the VSWR OUT was less than 1.6 for all attenuation states; insertion loss is less than 1.3dB; attenuation accuracy is less than ±0.26dB for all 35 attenuation states. The MMIC chip size is 0.93 mm×1.45 mm. This proposed MMIC has shown excellent performance covering DC~4GHz for digital attenuator.

REFERENCES

[1] Goldfarb, M.E.; Platzker, A., “A wide range analog MMIC attenuator with integral 180° phase shifter,” IEEE Trans. on Microwave Theory and Techniques, vol. 42, no.1, pp.156-158, 2007 http://dx.doi.org/10.1109/22.665545
[2] Yong-sheng Dai; Da-Gang Fang; Yong-Xin Guo, “A Novel UWB (0.045–50GHz) Digital/Analog Compatible MMIC Variable Attenuator With Low Insertion Phase Shift and Large Dynamic Range,” IEEE Trans. on Microwave and Wireless Components Letters, vol. 17, no.1, pp.61-63, 2007 http://dx.doi.org/10.1109/LMWC.2006.837263
[3] Baldwin, G.L.; McCrea, J., “An MOS Digitally Controlled Analog Attenuator for Voiceband Signals,” IEEE Trans. on Communications, vol. 27, no.2, pp.332-337, 1979 http://dx.doi.org/10.1109/TCOM.1979.1094538
[4] Granger-Jones, M.; Nelson, B.; Franzwa, E., “A broadband high-dynamic-range voltage-controlled attenuator MMIC with an IIP3 > +47 dBm over entire 30-dB analog control range,” in Proc. Microwave Symposium Digest, 2011, pp. 1.
[5] Hyunchul Eom; Kyounghoon Yang, “A 6-20 GHz compact multi-bit digital attenuator using InP/InGaAs PIN Diodes,” in Proc. Indium Phosphide and Related Materials, 2008, pp. 1-3.
[6] Xing Wen; Fa-Xin Yu; Ling-Ling Sun, “A Novel Ultra Broadband 8-45 GHz 4-Bit GaAs Pseudomorphic High Electron Mobility Transistors (pHEMT) Monolithic Digital Attenuator Used for Gain Control of Transceivers,” in Proc. Innovative Computing, Information and Control, 2009, pp. 519-522.
[7] Yong-sheng Dai; Jie Zhang; Bing-Qing Dai; Zhi-Dong Song; Gui-Xiang Qian; Shao-Bo Chen; Wen-Kan Zhou, “An ultra broadband 2–18GHz 6-bit PHEMT MMIC digital attenuator with low insertion phase shift,” in Proc. International Conference of Ultra-Wideband, 2010, pp. 1-3.
[8] Gupta, R.K.; Reynolds, J.H.; McNally, P.J., “Modeling and CAD of an Ultra-Broadband Monolithic 5-bit Digital Attenuator,” in Proc. Microwave Conference, 1988, pp.151-155.
[9] Inkwon Ju; Yoon-Sub Noh; In-Bok Yom, “Ultra broadband DC to 40 GHz 5-bit pHEMT MMIC digital attenuator,” in Proc. Microwave Conference, 2005, pp. 6.
[10] Takasu, H.; Sakakibara, C.; Okumura, M.; Kamihashi, S., “5-band MMIC digital attenuator with small phase variation,” in Proc. Microwave Conference, 1999, pp. 4.
[11] Sarkissian, J.C.; Delmond, M.; Laporte, E.; Rogeaux, E.; Soulard, R., “A Ku-band 6-bit digital attenuator with integrated serial to parallel converter,” IEEE Trans. on Microwave Symposium Digest, vol. 4, pp.1915-1918, 1999
[12] Radchenko, A.; Radchenko, V.; Kitchinsky, A.; Buterin, A., “Broadband Monolithic Digital Attenuator for X-Band Phased Array,” in Proc. Microwave and Telecommunication Technology, 2006, pp.201-202.
[13] Tolstolutsky, S.I.; Lee, A.I.; Kazatchkov, V.V.; Popov, M.A.; Tolstolutskaja, A.V.; Komor, V.P., “DC-4 GHz Band GaAs MMIC 4-Bit Digital Attenuator,” in Proc. Microwave and Telecommunication Technology, 2007, pp.85-86.
[14] Osipov, A.M.; Semyonova, I.M.; Radchenko, V.V., “5-6 GHz band GaAs MMIC five bit digital attenuator,” in Proc. Microwave & Telecommunication Technology, 2008, pp.118-119.
[15] Kinayman, N.; Bonilla, M.; Kelcourse, M.F.; Redus, J.; Anderson, K., “High-accuracy digital 5-bit 0.8-2 GHz MMIC RF attenuator for cellular phones,” IEEE Trans. on Microwave Symposium Digest, vol. 3, pp.2231-2234, 2001
[16] Krafcsik, D.; Ali, F.; Bishop, S.; Anderson, K., “Broadband, low-loss 5- and 6-bit digital attenuators,” IEEE Trans. on Microwave Symposium Digest, vol. 3, pp.1627-1630, 1995
[17] Lee, A.I.; Tolstolutsky, S.I.; Kazatchkov, V.V., “DC-2 GHz 4-bit digital MMIC attenuator with a small insertion phase,” in Proc. Microwave & Telecommunication Technology, 2008, pp.71-72.

AUTHORS

Chengpeng Liu is with the Sichuan Institute of Solid State Circuits, His research interests include GaAs MMIC and Si/SiGe RFIC for microwave and millimeter-wave applications. Chongqing, 400060 China (e-mail: lcp54913@163.com).

Wei Zou is with the Sichuan Institute of Solid State Circuit, Chongqing, 400060 China (e-mail: shenlandehai126.com).

Submitted 13 October 2013. Published as re-submitted by the authors 02 November 2013.