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A modulator using RF CMOS T-type attenuator for TH-UWB communications

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Abstract: The insertion loss (IL) of a T-type attenuator is theoretically analyzed. A T-type RF (radio frequency) CMOS (complementary metal-oxide-semiconductor) attenuator is designed as an on-off keying (OOK) modulator in a time-hopping ultra wide-band (TH-UWB) communication with a carrier frequency of 4 GHz. In the topology of the OOK modulator circuit, there are three parts, an oscillator with an oscillating frequency of 4 GHz, a T-type attenuator constructed by RF CMOS transistors, and an output impedance matching network with a L-type LC structure. The modulator is controlled by a time-hopping pulse position modulation (TH-PPM) signal. The envelope of the modulated signal varies with the amplitude of the controlling signal. Meanwhile, an output matching network is also designed to match a 50 Ω load. In 0.18 μm RF CMOS technology, a modulator is designed and simulated. The implemented modulator chip has 65 mV of the output amplitude at a 50 Ω load from a 1.8 V supply, and the return loss (S_{11}) at the output port is less than −10 dB. The chip size is 0.7 mm × 0.8 mm, and the power consumption is 12.3 mW.

Key words: attenuator; insertion loss (IL); on-off keying (OOK); RF CMOS

Ultra wideband (UWB) systems are particularly promising for short-range wireless communications as they potentially combine reduced complexity with low power consumption, low probability of intercept (LPI) and immunity to multi-path fading[1-3]. In UWB wireless communications, some pulses with variant amplitude such as Gaussian pulses are used as modulation signals to on-off keying (OOK) modulators. How to make the modulated signal to have the same envelope shape of the modulation signal in a CMOS technology is still a challenge. Some published papers have reported that FET attenuators are good candidates for achieving gain control with superior performance in various design criteria such as linearity and power handling requirements, which are extremely important for wideband applications such as cable modem receivers[4-7].

In this paper, utilizing the performance of a controllable FET attenuator's gain, a T-type attenuator used as an on-off keying modulator (OOK) for TH-UWB communications is analyzed and designed.

1 T-Type Attenuator Characteristics

In this section, the insertion loss (IL) and the relationship between the output voltage and the control voltage in a T-type attenuator are discussed.

1.1 Insertion loss

Fig. 1 shows the schematic of the minimum IL condition of a single-stage T-attenuator and the equivalent circuit model[7]. There is a minimum IL when the series devices are completely on and the shunt device is off, because the loss at lower frequencies results only from the nonzero on-resistance of the series devices. Caused by the parasitic capacitors to ground, there is an additional loss at a higher frequency.

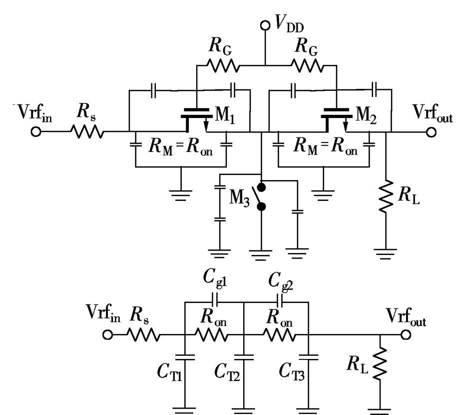

Fig. 1 Minimum insertion loss condition for a T-network and the equivalent circuit model

The parasitic capacitors are mainly formed by the gate capacitances of the devices, the junction capacitances between the drain and source implants, and the p-substrate of the chip[7]. In Ref. [7], the capacitances consist of the gate-oxide and junction parasitic capacitances of the devices mentioned above, and they can be expressed as

$$C_T = C_{T1} = C_{T3} = C_{db1} \tag{1}$$

$$C_g = C_{g1} = C_{g2} = \frac{C_{gd1}}{2} = \frac{C_{gs2}}{2} \tag{2}$$

$$C_{T2} = C_{sb1} + C_{db2} + C_{db3} + \frac{C_{gd3}}{2} \tag{3}$$

Let $R_s = R_L$, and the IL expression of the network can be written as[7]

$$L_I = \frac{R_s}{R_s + R_{on}} \frac{1}{1 + s\left(C_T R_s + C_{T2}\frac{R_s + R_{on}}{2}\right)} \tag{4}$$

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where R_{on} can be approximated by[2]

$$R_{on} = \frac{1 + \theta(V_{GS} - V_t)}{\mu C_{ox}(W/L)(V_{GS} - V_t - \eta V_{DS})} \tag{5}$$

where θ models the drain and source resistances, mobility degradation, and other short channel effects. The exponential increase of the drain current in the sub-threshold region is modeled by the parameter η.

1.2 Output voltage vs. controlling voltage

Fig. 2 shows the T-type attenuator circuit and its equivalent resistance circuit when the high frequency parasitic parameters are ignored.

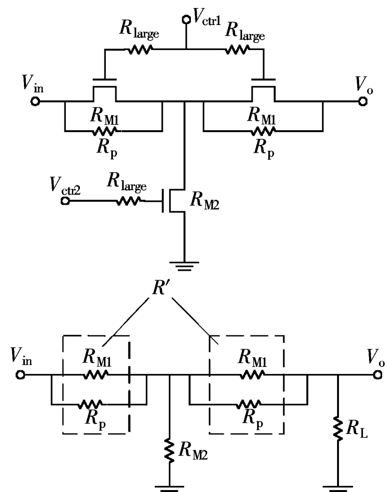

Fig. 2 Regular circuit and equivalent resistance circuit of T-type attenuator with limited insertion loss

From Fig. 2, utilizing KCL and KVL, we can derive the mathematic formula of the relationship between V_o and R' as follows:

$$V_o = \frac{R_{M2} R_L V_{in}}{R_{M2} + R' + R_L} \tag{6}$$

where $R' = R_{M1} // R_P$. According to Eq. (5), if ignoring θ and η, there are

$$R_{M1} = \frac{1}{\mu C_{ox}(W_1/L)(V_{ctrl} - V_t)} \tag{7}$$

$$R_{M2} = \frac{1}{\mu C_{ox}(W_2/L)(V_{ctr2} - V_t)} \tag{8}$$

So Eq. (6) can be expressed as

$$V_o = \frac{\frac{1}{\mu C_{ox}(W_2/L)V_{ctr2}} R_L V_{in}}{\frac{1}{\mu C_{ox}(W_2/L)V_{ctr2}} + R' + R_L} \tag{9}$$

When

$$R' = \frac{R_{M1} R_P}{R_{M1} + R_P} = \frac{\frac{1}{\mu C_{ox}(W_1/L)V_{ctrl}} R_P}{\frac{1}{\mu C_{ox}(W_1/L)V_{ctrl}} + R_p} \tag{10}$$

we obtain

$$V_o = \frac{R_L V_{in}}{1 + \frac{R_P \mu C_{ox}(W_2/L)V_{ctr2}}{1 + R_P \mu C_{ox}(W_1/L)V_{ctrl}} + \mu C_{ox}(W_2/L)V_{ctr2} R_L} \tag{11}$$

If the maximum amplitude of V_{ctrl} is V_m, let $V_{ctr2} = V_m - V_{ctrl}$, and then V_o can be expressed as

$$V_o = \frac{R_L V_{in}}{1 + \frac{R_P \mu C_{ox}(W_2/L)(V_m - V_{ctrl})}{1 + R_P \mu C_{ox}(W_1/L)V_{ctrl}} + \mu C_{ox}(W_2/L)(V_m - V_{ctrl})R_L} \tag{12}$$

This is the relationship between V_o and the controlling voltage. In order to simplify the computation, assuming that the value of R_P is very large, V_o can be written as

$$V_o = \frac{R_L V_{in}}{1 + \frac{W_2(V_m - V_{ctrl})}{W_1 V_{ctrl}} + \mu C_{ox}(W_2/L)(V_m - V_{ctrl})R_L} \tag{13}$$

Fig. 3 gives the relation curve of the output voltage vs. the controlling voltage when V_{in} is a constant. From the curve in Fig. 3, we can see that the output voltage linearly changes following the amplitude of the controlling voltage. If V_{in} is a sine wave, then the envelope of the output voltage changes following the amplitude of the controlling voltage.

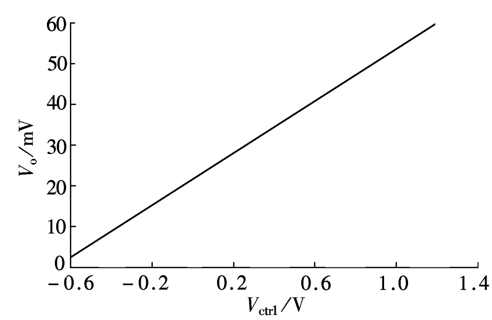

Fig. 3 Relation curve of the output voltage vs. the controlling voltage

2 Modulator Design Using A T-Type Attenuator

In the case of TH-UWB communications, an OOK modulation is one of the methods to realize frequency mapping. According to the characteristics of the relation curve of the output voltage vs. the controlling voltage in Fig. 3, we utilize a T-type attenuator to design an OOK modulator for the TH-UWB communication system. From Fig. 3 and Eq. (13), we can use the controlling voltage as a modulation signal, the input signal of the attenuator as a carrier, and then the output signal of the attenuator is an OOK signal.

2.1 Design method

Fig. 4 shows the design method of an OOK modulator with a T-type attenuator. The OOK modulator consists of an oscillator, a T-attenuator, and an output matching network. From the schematic in Fig. 4, it can be seen that the T-type

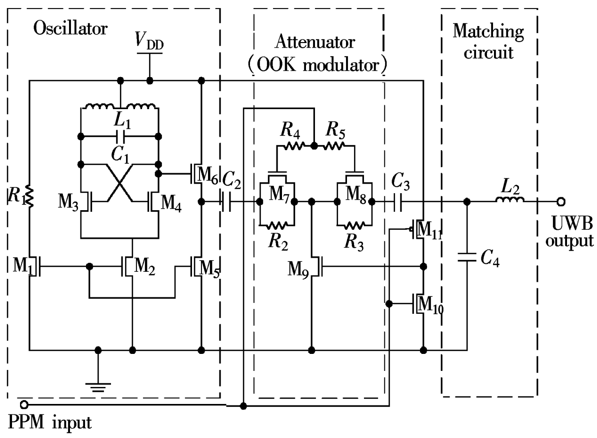

Fig. 4 OOK modulator circuit with T-type attenuator

CMOS attenuator is used as the OOK modulator. Its insertion loss value is controlled by design parameters.

The oscillator, which consists of RF CMOS transistors and an LC network, generates a sinusoidal signal with a frequency of 4 GHz. The output matching circuit is used to match the impedance of the CMOS attenuator to 50 Ω in order to transmit the UWB signal to an antenna through a 50 Ω transmission line.

2. 2 Attenuator parameter design

As shown in Fig. 4, the T-type attenuator has a small insert loss when the controlling voltage is at a high voltage level; otherwise, the T-type attenuator has a large insert loss when there is a low voltage level. In Fig. 4, the T-type attenuator is composed of M_7, M_8, M_9(FET), R_2, R_3, R_4 and R_5(resistance). From Eq. (13), we know that the *W/L* of M_7, M_8, M_9 and the resistance of R_2 and R_3 are critical. These parameters have a direct effect on the amplitude of the output signal of the modulator. In this design, the key parameters are as follows. M_7 and M_8: $W = 160$ μm, $L = 180$ nm; M_9: $W = 200$ μm, $L = 180$ nm. $R_2 = R_3 = 100$ Ω. The modulator is implemented by SMIC's 0. 18-μm RF CMOS.

2. 3 Simulation and experiment

Fig. 5 shows the chip photograph of the OOK modulator. The T-type attenuator is marked out by a rectangular block. The chip size is 0. 7 mm × 0. 8 mm.

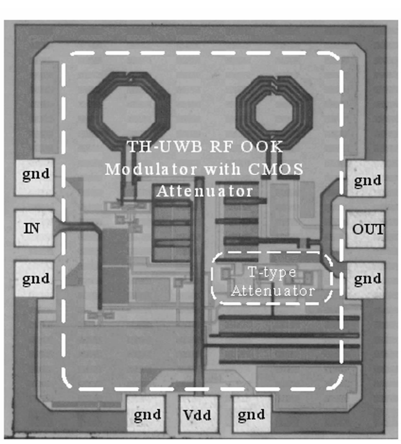

Fig. 5 Chip photograph

Fig. 6 shows the measured TH-PPM input signal and the TH-UWB output signal. A Gaussian pulse-shape is used as a TH-PPM pulse and the TH-UWB output signal amplitude is about 65 mV. Both signals are measured by an Agilent infiniium DCA 86100A wide-bandwidth oscilloscope. The frequency from the oscillator measured by an Agilent E4440 frequency spectrum analyzer is 3. 876 9 GHz. Compared with the simulation results, there is a difference of 123. 1 MHz. This is because the proposed oscillator is not a VCO, and the process deviation is ineluctable. When we use an envelope detector to demodulate this signal, such a frequency deviation is insignificant.

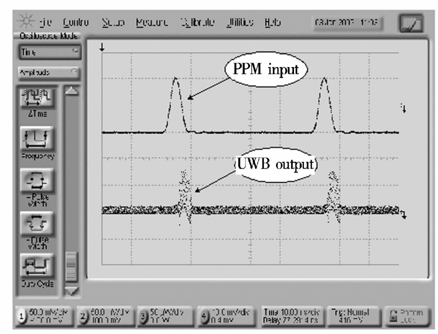

Fig. 6 Measured waveforms

The output matching circuit is used to match the impedance of the CMOS attenuator to 50 Ω in order to transmit the UWB signal to an antenna through a 50 Ω transmission line. An important parameter to evaluate the impedance matching is the return loss parameter, i. e. S_{11}. Generally, S_{11} should be less than − 10 dB.

Fig. 7 shows the simulated and measured S_{11} at the output port. The results show that both values are less than − 10 dB. From the results in Fig. 7, the simulated S_{11} is flattened over the given frequency range, i. e. from − 14 to − 16 dB. Compared with the simulated curve, the measured S_{11} has more difference, i. e. from − 10 to − 17 dB. This difference may be due to the effects of the parasitic parameters of the chip.

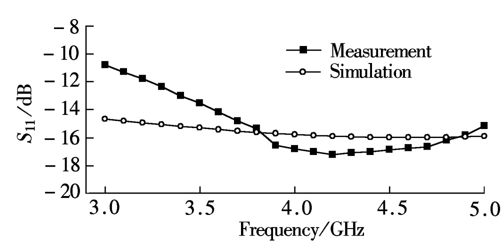

Fig. 7 Simulated and measured S_{11}

3 Conclusion

Through the analysis on T-type attenuator networks and the design of the OOK modulator using a T-type attenuator, we realize the application of a T-type CMOS attenuator. The results of the simulation and measurement show that the modulator chip has an output amplitude of 65 mV at a 50 Ω load from a 1. 8 V supply; the return loss (S_{11}) at the output port is less than − 10 dB, and the power consumption is 12. 3 mW.

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采用 RF CMOS T 型衰减器的 TH-UWB 通信调制器

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摘要：对 T 型衰减器的插入损耗和衰减性能进行了理论分析，在此基础上设计了一个用于跳时超宽带(TH-UWB)通信的载波频率为 4 GHz 的通断键控(OOK)调制器. 该调制器的核心是一个 T 型 RF CMOS 衰减器，其电路拓扑结构包括 3 个主要部分：振荡频率为 4 GHz 的振荡器、由射频 CMOS 晶体管构成的 T 型衰减器和带有 L 型结构的输出阻抗匹配网络. 该调制器由一个脉位调制(PPM)信号控制，使已调信号的包络随控制信号的幅度而变化，以实现调制功能. 除此之外，输出匹配网络将调制器的输出阻抗匹配到 50 Ω 负载. 调制器采用 0.18 μm 射频 CMOS 工艺进行设计并仿真，其芯片经过测试，在 1.8 V 电源和 50 Ω 负载下有 65 mV 的输出幅度，输出端回波损耗(S_{11})小于 −10 dB，功耗为 12.3 mW，芯片尺寸为 0.7 mm × 0.8 mm.

关键词：衰减器；插入损耗；通断键控(OOK)；射频 CMOS

中图分类号：TN402