Wideband attenuators using distributed resistors for attenuation up to 30 dB

Qi Zhong\(^{a)}\) and Zewen Liu

Institute of Microelectronics, Tsinghua University, Beijing 100084, China

a) zhongq13@mails.tsinghua.edu.cn

Abstract: In this paper, attenuators with distributed resistor networks for attenuation up to 30 dB from DC to 25 GHz are presented. The distributed thin-film resistor network is embedded in coplanar waveguide (CPW) for microwave application. The sheet resistance and size of distributed thin-film resistor network are accurately calculated by conformal mapping and elliptic function for corresponding attenuation. The achieved attenuators is based on the use of tantalum-nitride (TaN) thin-film resistors with low mean temperature coefficient of resistance (TCR), high resistance silicon substrate and Au CPW. Microwave testing results show excellent performance with return losses better than 27 dB and insertion losses of 10.23 ± 0.12 dB, 15.23 ± 0.18 dB, 20.09 ± 0.23 dB and 29.17 ± 0.55 dB in the interesting frequency range.

Keywords: attenuator, distributed resistor, wideband, tantalum-nitride thin-film resistor

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

[1] J. L. Cano, et al.: “Ultra-wideband chip attenuator for precise noise measurements at cryogenic temperatures,” IEEE Trans. Microw. Theory Techn. 58 (2010) 2504 (DOI: 10.1109/TMTT.2010.2058276).

[2] A. Effendy and A. Ali: “The design of 5 dB attenuator in coplanar waveguide for DC to 67 GHz,” 2011 IEEE International RF and Microwave Conference (RFM) (2011) 246 (DOI: 10.1109/RFM.2011.6168740).

[3] N. D. Cuong, et al.: “Ti (n) thin film resistors for 20 dB pi-type attenuator applications,” Appl. Phys. Lett. 90 (2007) 183506 (DOI: 10.1063/1.2734899).

[4] Y. Sun, et al.: “Attenuators using thin film resistors for RF application,” 2008 International Conference on Electronic Packaging Technology & High Density Packaging (2008) 1 (DOI: 10.1109/ICEPT.2008.4607011).

[5] S. Otto, et al.: “A distributed attenuator for K-band using standard SMD thin-film chip resistors,” Asia Pacific Microwave Conference, 2009. APMC 2009 (2009) 2148 (DOI: 10.1109/APMC.2009.5385509).

[6] R. S. Johnson, et al.: “Frequency response of thin film chip resistor,” Proc. of the 25th CARTS USA 2005 (2005) 136.

[7] R. J. Dow: “Synthesis of multiple resistance networks from single resistive films,” IEEE Trans. Compon. Parts 10 (1963) 147 (DOI: 10.1109/TPC.1963.1134821).
1 Introduction

Nowadays, attenuators are widely used in radar system and wireless communication system for adjusting signal power and impedance matching [1, 2, 3, 4, 5]. The step attenuators consist of constant insertion loss attenuators and single-pole-double-throw (SPDT) switches have the advantages of low cost and flexible design. The constant insertion loss attenuators can be fabricated using SMD thin film resistor chip process [1, 2, 4]. But for the high insertion loss (20 dB, for example), the resistance of resistors are so big that thin-film resistors with high length-width ratio will introduced parasitic capacitance and inductance which extremely restrict the bandwidth [6]. One way to avoid this is to use low insertion loss attenuators cascade as high one [1, 4]. But this method will obviously increase the chip size.

Another way is to use distributed thin-film resistor networks to compose attenuators [7, 8, 9, 10]. The resistors existing between electrodes of distributed network can be equivalent to the resistors in π or T-type network. Due to the properties of distributed networks, the thin-film resistors with relatively low length-width ratio can also get high resistance so that the parasitic capacitance will be decreased. In this paper, the design method of small-size, wideband thin-film resistor attenuators is discussed. The symmetrical distributed network is embedded in CPW to improve the microwave performance for the first time. Design method, fabrication process and measured results of a series of sample attenuators with high attenuation are given. Measured results show that the attenuators provide both good linearity and precision of insertion loss and matches the input and output impedances from DC to 25 GHz.

2 Design of attenuators

2.1 Design of π-type resistive attenuation networks

The π- and T-type resistive attenuation networks are composed by parallel and series resistors shown in Fig. 1(a)~Fig. 1(b) [4]. The function of distributed resistive networks can be equivalent to either π-type networks or T-type networks. To simplify the description, distributed resistive attenuation networks are equivalent to π-type networks in this paper. The relationship between $R_p$, $R_s$ and S-parameter obey the Eq. (1), Eq. (2) corresponding to π-type networks, where $A$ (dB) stands for attenuation. The values of resistors calculated via Eq. (1) and Eq. (2) are shown in Table I for 10 dB, 15 dB, 20 dB, 30 dB attenuator.
For the lumped resistors $\pi$-type attenuators, the resistors with two terminals is embedded in transmission (shown in Fig. 2 as an example). The values of resistors are determined by the length-width ratio and the sheet resistance of thin film resistors. For the certain size of transmission line and sheet resistance, the design method of this type of attenuators is to adjust the width of thin film resistors to meet the requirement of insertion loss and return loss. To increase the return loss and flatness of insertion loss, the length and width of $R_s$ and $R_p$ need to be adjusted for decreasing the influence of parasitic capacitance and inductance. But for the high attenuation, the $R_s$ need to be increased, which will further unavoidable result in larger parasitic capacitance and inductance. And this will limit the high frequency performance of attenuator. In order to increase performance and decrease the size, the following design method is introduced.

$$R_s = Z_0 \frac{1 + 10^{-\frac{A}{20}}}{1 - 10^{-\frac{A}{20}}}$$  \hspace{1cm} (1)

$$R_p = Z_0 \frac{1 - 10^{-\frac{A}{10}}}{2 \times 10^{-\frac{A}{10}}}$$  \hspace{1cm} (2)

For the lumped resistors $\pi$-type attenuators, the resistors with two terminals is embedded in transmission (shown in Fig. 2 as an example). The values of resistors are determined by the length-width ratio and the sheet resistance of thin film resistors. For the certain size of transmission line and sheet resistance, the design method of this type of attenuators is to adjust the width of thin film resistors to meet the requirement of insertion loss and return loss. To increase the return loss and flatness of insertion loss, the length and width of $R_s$ and $R_p$ need to be adjusted for decreasing the influence of parasitic capacitance and inductance. But for the high attenuation, the $R_s$ need to be increased, which will further unavoidable result in larger parasitic capacitance and inductance. And this will limit the high frequency performance of attenuator. In order to increase performance and decrease the size, the following design method is introduced.

**Table I.** Values of resistors

| Attenuation (dB) | 10    | 15    | 20    | 30    |
|------------------|-------|-------|-------|-------|
| $R_p$ (Ω)        | 96.25 | 71.63 | 61.11 | 53.27 |
| $R_s$ (Ω)        | 71.15 | 136.14| 247.50| 789.78|

**Fig. 2.** Lumped resistors $\pi$-type attenuator.

### 2.2 Design of distributed network

The distributed resistor network attenuator is made up of two main components: coplanar waveguide (CPW) and thin film resistor network embedded in CPW, as shown in Fig. 3. The resistors existing between the electrodes of thin film resistor
network form network structure which can be equivalent to π-type. Considering the symmetry of this network, the $R_p$ of π-type network is divided into two parallel $2R_p$ resistors, while the $R_s$ is divided into two parallel $2R_s$ resistors (Fig. 3).

![Fig. 3. π-type equivalent circuit of distributed resistor network attenuator.](image)

Fig. 3. π-type equivalent circuit of distributed resistor network attenuator.

Obviously, this network can be divided into two same parts, as shown in Fig. 4 [9]. $R_{sc}$ is the input resistance of the RF-in terminal when the RF-out terminal and ground are short circuited, while the $R_{oc}$ is the input resistance when the RF-out terminal and ground are open circuited. The resistance of $R_p$ and $R_s$ can be calculated from Eq. (3) and Eq. (4) via $R_{sc}$ and $R_{oc}$ [8].

$$R_s = \frac{R_{sc}\sqrt{R_{oc}}}{2\sqrt{R_{oc} - R_{sc}}}$$  \hspace{1cm} (3)

$$R_p = \frac{R_{oc} + \sqrt{R_{oc}^2 - R_{oc}R_{sc}}}{2}$$  \hspace{1cm} (4)

To obtain the $R_{sc}$ and $R_{oc}$, the network in Fig. 4 is further divided into two same parts based on symmetry and one of them is named $R_{och}$, as shown in Fig. 5(a). According to the Bartlett’s bisection theorem [8], another resistive circuit is introduced and named as $R_{sch}$ as shown in Fig. 6(b). The resistance of $R_{oc}$ and $R_{sc}$ can be calculated from Eq. (5) via $R_{och}$ and $R_{sch}$ [8].

$$R_{sc} = \frac{2R_{sch}R_{och}}{R_{sch} + R_{och}}, \quad R_{oc} = \frac{R_{och} + R_{sch}}{2}$$  \hspace{1cm} (5)

Four steps of conformal mappings are introduced to calculate the resistance of $R_{och}$ and $R_{sch}$. A universal method is given in [7] used to calculate the resistance of rectangular thin film resistor with two irregular electrodes shown in Fig. 6(a). POQ and SBR are ideal metal electrodes while OABC is rectangular thin film resistor with sheet resistor $\rho$ in z-plane. At first, OABC is mapped to the upper half of
t-plane using Eq. (6) [7] shown in Fig. 6(a) to (b). sn is abbreviated form of Jacobi elliptic function and $K$ is the real quarter period of the elliptic modulus $k$ while $K'$ is the imaginary quarter period. Parameter $m$ is $K/l = K'/l'$.

\[
t = \text{sn}^2(mz, k)
\]

As shown in Fig. 6(b) to (c), second transformation is from t-plane to μ-plane using Eq. (7) [7],

\[
\mu = \frac{\delta - \beta}{\beta - \alpha} \cdot \frac{t - \alpha}{\delta - t}
\]

where the $\alpha$, $\beta$, $\gamma$, and $\delta$ are given by Eq. (8) [7].

\[
\alpha = \text{sn}^2(mp, k), \quad \beta = \text{sn}^2(mq, k), \quad \gamma = \text{sn}^2(mr, k), \quad \delta = \text{sn}^2(ms, k)
\]

As shown in Fig. 6(c) to (d), the final conformal mapping is introduced by the Eq. (9) [7],

\[
\chi = \text{sn}^{-1}(\mu, \lambda)
\]

where $L$ is the real quarter period of the elliptic modulus $\lambda$ and $L'$ is the imaginary quarter period. $\lambda$ is given by (10) [7].
Because of conformal map, the magnitude and sense of angles between equipotential lines and current lines are reserved. The resistance of thin film resistance in both Fig. 6(a) and (d) can be got by $L'/L$ [7]. The values of $\rho$ and $l$ of 10 dB, 15 dB, 20 dB and 30 dB attenuator have been calculated and shown in Table II for the CPW dimension in Fig. 7. The full wave EM simulator is used to verify and adjust the design.

$$\frac{1}{\lambda^2} = \frac{\delta - \beta}{\beta - \alpha} \cdot \frac{\gamma - \alpha}{\delta - \gamma}$$ (10)

| Attenuation (dB) | 10  | 15  | 20  | 30  |
|------------------|-----|-----|-----|-----|
| Sheet Resistance $\rho$ (\(\Omega\)) | 91.64 | 92.08 | 92.24 | 92.30 |
| $l$ (\(\mu m\)) | 90.96 | 140.21 | 189.65 | 288.58 |

Fig. 7. Dimensions of CPW designed for testing in a probe station, multilayer structure designed for fabrication process. (a) Planform of CPW, (b) sectional view of CPW.

### 3 Fabrication

The high resistance silicon is widely used as substrate of radio frequency micro-electromechanical system (RF MEMS) components such as switches and varactor. This material has low dielectric loss and high processing compatibility to make the attenuators connect with the RF MEMS components easily. The attenuator designed in this paper is fabricated on a 3" 500-\(\mu m\)-thick N-type(100)-oriented high resistance silicon substrate ($\varepsilon_r = 11.9$) using a TaN resistor process.

Fig. 8. Process flow. (a) SiO$_2$ buffer layer, (b) TaN resistor layer, (c) TiW/Au seed and adhesive layer, (d) Au layer, (e) etching TaN layer, (f) etching TiW/Au layer.
First, a 300-nm-thick SiO$_2$ layer is thermal oxidized on the surface as the buffer layer (Fig. 8). Next, a 100-nm-thick TaN layer is sputtered on the top of the substrate as the resistor material. A 100-nm-thick TiW/Au is next sputtered to create seed layer and adhesive layer. Next, a 2-µm-thick Au layer is patterned to create transmission line using AZ6130 as the plating mould. Redundant seed layer and TaN are removed by wet-etching process. At last, a Ta$_2$O$_5$ layer is thermal oxidized on the TaN layer for adjusting sheet resistance and protective layer. The fabricated attenuators are shown in Fig. 9(a)–Fig. 9(d).

4 Measurements and analysis

4.1 Sheet resistance measurements and analysis

The sheet resistance of the TaN resistors is 97.4 Ω at 20°C tested by Agilent Technologies B1500A semiconductor device parameter analyzer and Cascade Microtech Summit 11000M probe system. The variation of attenuation can be got via the variation of resistance correspondingly. The mathematical analysis by Eq. (11) and Eq. (12) manifests that the variation of attenuation is within ±0.5% compared to design value and the insertion loss is above 37 dB. The $\rho = 92$ Ω is design sheet resistance and $\rho'$ is tested sheet resistance. The variation of sheet resistance between −50°C and 50°C is shown in Fig. 10. Mean temperature coefficient of resistance (TCR) is 343 ppm/°C.

\[
S_{11} = \frac{R_sR_p^2\rho'^2 - 2Z_0^2R_p - Z_0^2R_s}{2(Z_0R_p^2\rho' + R_pR_s\rho'Z_0) + R_sR_p^2\rho'^2 + 2Z_0^2R_p + Z_0^2R_s}
\]  
(11)

\[
S_{21} = \frac{2Z_0R_p^2\rho'}{2(Z_0R_p^2\rho' + R_pR_s\rho'Z_0) + R_sR_p^2\rho'^2 + 2Z_0^2R_p + Z_0^2R_s}
\]  
(12)
4.2 Microwave performance measurements

The attenuators are measured with the Agilent Technologies PNA-X N5247A Vector network analyzer and Cascade Microtech Summit 11000M probe system. The tested S-parameter of 5 dB, 10 dB and 20 dB as show in Fig. 11 and Fig. 12 respectively. The VNA and probe system are connected by the coaxial line which limit the testing range from DC to 25 GHz. In whole frequency range, the tested attenuation are $10.23 \pm 0.12$ dB, $15.23 \pm 0.18$ dB, $20.09 \pm 0.23$ dB and $29.17 \pm 0.55$ dB respectively and the return loss of all the elements are better than 27 dB.

![Graph showing sheet resistance vs temperature](image1.png)

**Fig. 10.** Sheet resistance between $-50 ^\circ$C and $50 ^\circ$C.

![Graph showing S11 vs frequency](image2.png)

**Fig. 11.** Measured $S_{11}$ of attenuators at room temperature.
5 Conclusion

In this paper, a method to design wideband distributed thin-film resistor attenuator has been proposed and 10 dB, 15 dB, 20 dB, 30 dB attenuator have been fabricated in the thin film resistor process. The TCR and microwave test results along with analysis are given. The chip size is smaller and the microwave performance is better than the structure in Fig. 2. Attenuators designed and fabricated by this method can be used either standalone or linked by SPTD switches. This design method can be expended to other transmission line such as microstrip line, and the thin film resistors can use other materials such as Ni-Cr alloy and polycrystalline silicon.

Acknowledgments

This work was supported by the Tsinghua University Initiative Scientific Research Program, Grant No 20121087907.

Fig. 12. Measured $S_{21}$ of attenuators at room temperature.