Reconfigurable dual-band power amplifier based on memristor

Zhiwei Zhang1, Zhiqun Cheng1, a), Huajie Ke1, and Guohua Liu1

Abstract This letter presents a reconfigurable dual-band power amplifier based on memristor. The memristor is first applied in the field of RF power amplifier design. Based on the basic theory of memristor, different values of the resistance of the memristor are obtained by adding different dc voltages on the memristor, and conversion between different output matching circuits is realized. Thus, a reconfigurable output matching circuit is constructed to realize a reconfigurable dual-band power amplifier. To verify the effectiveness of the proposed method, a reconfigurable dual-band power amplifier is designed and simulated. The simulation results show that by setting different dc voltages of the memristor, the saturated output power of 41 dBm and drain efficiency of more than 70% can be achieved at two frequency points of 2.0 GHz and 3.0 GHz, and the gain can reach 10 dB.

Keywords: reconfigurable, dual band, power amplifier, memristor

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

1. Introduction

Wireless communication technology is developing rapidly [1, 2, 3, 4, 5]. In order to support larger transmission bandwidths, multiple methods have been proposed [6, 7, 8, 9, 10]. However, in modern communication systems, the frequency band often used is the frequency range of up to 100–200 MHz near the corresponding center frequency [11, 12, 13]. Broadband power amplifiers (PAs) often cover frequency points that are not needed for communication, which is a waste of resources to some extent. It also causes the non-ideal performance of the PA at the actual operating frequency range [14, 15]. In order to solve these problems, reconfigurable PAs supporting multi-band operation have been proposed [16, 17, 18, 19, 20, 21, 22]. In [16, 17, 18], dual-band Doherty PA is presented by using diodes. Another reconfigurable PA that supports multi-band operation is introduced by choosing appropriate micro-strip transmission line [19, 20, 21]. A reconfigurable Class AB PA is designed with an adaptive matching network by applying shunt MEMS switches [22]. However, the reconfigurable multi-band PAs formed by the above methods usually cannot operate with optimal performance at the required frequency range because the micro-strip line, the diode or the MEMS switches all have parasitic parameters that vary with frequency. This frequency dependent effect affects the accuracy of the matching circuit, and then in turn deteriorates the performance of PAs. In addition, diodes and MEMS switches require continuous power supply, which causes a certain waste of energy.

In order to solve the problems of traditional reconfigurable PAs, this paper proposes a dual band reconfigurable PA by using memristor. The new device “memristor” is firstly used as the core component of a reconfigurable active matching circuit. The resistance of the memristor is changed by tuning the dc bias voltages across the memristor. Based on this, a reconfigurable output matching circuit that adapts to different frequency bands is designed. For validation, a reconfigurable PA operating at 2.0 GHz and 3.0 GHz is designed and simulated.

2. Theoretical analysis

Leon Chua first predicts the existence of a memristor (M) mathematically in 1971 [23]. The memristor is called the fourth basic passive electrical components after resistor (R), capacitor (C), and inductor (L). Leon Chua propose three characteristic conditions for determining a device called a memristor [24, 25], where the third “as the frequency tends to infinity, the hysteresis loop curve shrinks to a straight line through the origin”. It means that the resistance of the memristor is close to the linear resistance at high frequencies, which builds the foundation for its application in high frequency situations.

In 2008, HP Laboratories successfully develop a nanoscale solid-state device with complete physical properties, whose physical model can be seen in Fig. 1 [26]. The application of an external bias \(v(t)\) across the device will move the boundary between the two regions by causing the charged dopants to drift. The port equation and state equation are expressed as:

\[
v(t) = \left( R_{on} + R_{off} \right) \frac{w(t)}{D} \text{ diode current } i(t)
\]

\[
\frac{dw(t)}{dt} = \frac{w(t)(D - w(t))}{D^2} \cdot \mu_v \frac{R_{on}}{D} i(t)
\]

where \(w(t)(D - w(t))/D^2\) is a window function. The \(\mu_v\) is

---

1 Key Lab. of RF Circuit and System, Education Ministry, Hangzhou Dianzi University, Hangzhou 310018, China

a) zhiqun@hdu.edu.cn

DOI: 10.1587/elex.17.20200171

Received May 7, 2020
Accepted May 13, 2020
Publicized May 26, 2020
Copyedited June 10, 2020

Copyright © 2020 The Institute of Electronics, Information and Communication Engineers
the ion drift mobility. $R_{on}$ represents the resistance of the doped region when the entire memristor is filled, and $R_{off}$ represents the resistance of the undoped region when the entire memristor is filled. $w$ and $D$ denote the thickness of the doped region and the sandwiched between two metal contacts, as shown in Fig. 1.

Let $x = w(t)/D$, $k = \mu_v R_{on}/D^2$. Eq. (1) and (2) can be simplified as:

$$v(t) = R_{off} \cdot i(t) + (R_{on} - R_{off}) \cdot x \cdot i(t) \tag{3}$$

$$\frac{dx(t)}{dt} = k x(t)(1 - x(t)) \cdot i(t) \tag{4}$$

Its memristance value $M$ can be derived as:

$$M(t) = \frac{v(t)}{i(t)} = R_{off} + (R_{off} - R_{on}) \cdot x \tag{5}$$

We should solve Eq. (3) and (4) to obtain features of memristor. In this work, the simple model of memristor is built based on (3) and (4), as shown in Fig. 2 [27]. In Fig. 2, a simple series of the resistor $R_{off}$ and the other special negative resistor with time-dependent state variable ($(R_{on} - R_{off}) \cdot x(t)$) are used to model the port equation (3). In order to solve the differential state equation (4), an integrator can be designed and modeled when it is written in an integral form.

$$x(t) = \int k x(t)(1 - x(t)) \cdot i(t)dt + x_0 \tag{6}$$

where $x_0$ is the initial state of $x(t)$.

The integrator can be designed by using model described in [28, 29]. This kind of integrator only consists of one capacitor, one resistor, one current dependent current source, and one VDVS, shown in Fig. 2.

The voltage relationship between input and output in Fig. 2 can be expressed as:

$$V_{out} = \frac{1}{RC} \int V_{in}(t)dt + V_0 \tag{7}$$

where $V_0$ is the initial voltage. From Eq. (7), it is clearly that this equation can replace the integral form of Eq. (4) if $RC = 1s$.

The parameters of the simple memristor model are set as follows: $RC = 1s$, $R_{off} = 10k\Omega$, $R_{on} = 100\Omega$, $k = 10^{12}$. The initial state value $x_0$ is set to $x_0 = 0.05$. The simple memristor model shown in Fig. 2 can be described in SPICE code.

Its SPICE codes are shown as follows:

*The port equation
Roff 1 2 10k
V1 2 0 V = (I(V1))*(-9900)*I(V(40))
*The state equation
V2 0 10 V = (V(40))*(-1-V(40))*1e12*I(V1)
R1 10 0 1

![Fig. 2 Simple memristor model](image)

**Fig. 2** Simple memristor model

![Fig. 3 (a) Simulated memristor instantaneous i-v characteristic curve, where $f_0 = 100\text{MHz}$. (b) Time-dependent memristance $R_{mem}$ driven by sinusoidal voltage $\sin(2\pi \cdot 10^7 t)$.](image)

I3 0 30 1 = I(V2)
C1 0 30 1 IC = 0.05 V
E1 40 0 0 30 1
.TRAN 0 800 ns 0.01 ns UIC
.END

In order to enable the memristor to be used in microwave PA design, the circuit model of the memristor should be formed in the Advanced Design System (ADS) software. Fortunately, ADS software supports the components described by the SPICE code. Therefore, a memristor circuit component can be established from an appendix-based SPICE code in ADS software. In order to verify that the memristor described by SPICE can exhibit normal performance, the simulation is performed in ADS environment. The instantaneous i-v characteristic curve is simulated first. We can clearly see from Fig. 3(a) that i-v characteristic curve gradually becomes linear, as the frequency of the drive signal increases. It conforms to the third characteristic condition of the memristor and is suitable for applications in the microwave field. Time-dependent memristance $R_{mem}$ is also simulated.

Fig. 3(b) shows the time-varying memristor value for a sinusoidal driving voltage of $\sin(2\pi \cdot 10^7 t)$. It is significant
that the memristance $R_{\text{mem}}$ can be changed from $R_{\text{off}}$ to $R_{\text{on}}$ during a very short period about 50 ns, and the reverse is similar. Also, memristance $R_{\text{mem}}$ is $R_{\text{off}}$ about 10 k$\Omega$ with a 1 V voltage, and memristance $R_{\text{mem}}$ is $R_{\text{on}}$ around 10 $\Omega$ with a $-1$ V voltage. This makes it possible to control the resistance of the memristor by changing the voltage across memristor. Next, a reconfigurable matching circuit will be designed based on this characteristic of memristor.

3. Experiment and results

Based on the memristor built in the previous section, this paper introduces a reconfigurable matching circuit that supports two center frequencies. Then a reconfigurable dual-band power amplifier is designed. The PA uses the CGH40010F GaN HEMT based on the Rogers 4350B substrate [30]. The dc bias voltages are set to be 28 V at the drain and $-2.7$ V at the gate, respectively. The optimal load impedances are $12.638 + j * 10.21$ at 2.8 GHz, and $11.673 + j * 12.234$ at 1.8 GHz obtained by the load-pull in ADS software. The most important part of this work is to design the reconfigurable output matching circuit. The basic circuit topology is shown in Fig. 4. Microstrip lines TL1, TL2, TL4 and TL5 are located on the main path, while microstrip lines TL3, TL31, TL32, dc blocking capacitors and memristor M1 are on the branch. In this paper, the resistance value is mainly controlled by the dc bias voltage across the memristor. The two extreme values of memristance are considered in this work. One is the $R_{\text{off}}$ of 10 k$\Omega$, the other is the $R_{\text{on}}$ of 10 $\Omega$. Actually, the memristor does not dissipate any power except during the brief switching time intervals. Compared with the traditional RF switches, the memristor-based reconfigurable PA does not require a continuous power supply and consumes little energy. This is due to the fact that the memristance value is related to the former voltage of memristor. In other words, its resistance value remains unchanged, even when the dc voltage is removed. The resistance of the memristor changes only when a voltage of the opposite polarity is applied again.

When the resistance of the memristor is about $R_{\text{off}}$ 10 K$\Omega$ with 1 V dc voltage applying, the branch is almost open at this time. In this case, the output matching circuit operates at 3 GHz by adjusting the main path microstrip lines TL1, TL2, TL4 and TL5. Its matching impedance trajectory is shown in Fig. 4(b). When the dc voltage of $-1$ V is applied across the memristor, the state of the memristor turns to $R_{\text{on}}$ rapidly, meaning that its memristor value quickly becomes 10 $\Omega$. At this time, the branch is almost short, and the microstrip line TL3, TL31 and TL32 start to affect the impedance of the output matching circuit. By adjusting the characteristic impedance and the phase of microstrip line TL3, TL31 and TL32, the output matching circuit can operate at 2 GHz. Its impedance trajectory is also shown in Fig. 4.

In order to simplify the design process, only the output matching circuit is designed in a reconfigurable form. The input matching circuit is still designed as covering the entire frequency band of 1.8–3.2 GHz by stepped impedance matching. The designed output matching, input matching circuit and dc bias circuit are included in a complete PA circuit diagram. The completed circuit schematic is shown in Fig. 5.

Simulation of the large signal performance of the overall circuit yields the results shown in Fig. 6. It can be observed
from Fig. 6(a) that the designed PA operates at 3 GHz with 1 V dc voltage applied across the memristor. Its saturated output power is 41 dBm, the drain efficiency is 70%, and the gain is greater than 10 dB. As shown in Fig. 6(b), when –1 V dc voltage is added, the designed PA operates at 2 GHz, and its saturated output power can still reach 41 dB, the drain efficiency is 72%, and the gain is 10.5 dB. These simulated results demonstrate that the memristor-based reconfigurable PA can operate well at 2 GHz and 3 GHz after applying 1 V and –1 V voltage on memristor. It should be noted that the dual-band PA formed by memristor could reduce power consumption compared to the traditional use of diodes. This is due to the characteristic that the memristor does not require continuous power supply. Opposite polarity voltage should be given only when switching the operating frequency. At present, real memristors are still difficult to obtain, especially at high frequencies. Therefore, in this paper, only simulation is performed.

4. Conclusion

In this letter, based on the new component “memristor”, a reconfigurable dual-band PA is presented. By controlling the dc voltage exerted on the memristor, the memristance value of the memristor is approximately open or short. Then, a reconfigurable dual-band PA can be realized by controlling the switching of the output matching circuit branch. The simulation results show that the designed reconfigurable PA can work well at both 2 GHz and 3 GHz after adding –1 V and 1 V dc voltage on memristor, respectively. The saturated output power of 41 dBm can be obtained at the two frequencies, with greater than 70% drain efficiency. The gain is more than 10 dB. The simulation results demonstrate that a possible application of memristors is in the RF/microwave reconfigurable PA design.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant 61871169 and Grant 91938201) and the Zhejiang Provincial Natural Science Foundation (Grant LZZ20F010004).

References

[1] M.-J. Hsiao, et al.: “On the investigation of cascode power amplifiers for 5G applications,” Microw. Opt. Techn. Lett. 61 (2019) 1774 (DOI: 10.1002/mop.31761).
[2] S. Hu, et al.: “A 28-37/39-GHz linear Doherty power amplifier in silicon for 5G applications,” IEEE J. Solid-State Circuits 54 (2019) 1586 (DOI: 10.1109/JSSC.2019.2920307).
[3] Z. Yang, et al.: “Bandwidth extension of Doherty power amplifier using complex combining load with noninfinite peaking impedance,” IEEE Trans. Microw. Theory Techn. 67 (2019) 765 (DOI: 10.1109/TMTT.2018.2884415).
[4] J. Pang, et al.: “Design of a post-matching asymmetric Doherty power amplifier for broadband applications,” IEEE Micro. Wireless Compon. Lett. 26 (2016) 52 (DOI: 10.1109/LMWC.2015.2505651).
[5] X. Ding, et al.: “2–4 GHz wideband power amplifier with ultra-flat gain and high PAE,” Electron. Lett. 49 (2013) 326 (DOI: 10.1049/el.2012.4135).
[6] C. Shen, et al.: “Design of broadband high-efficiency Doherty power amplifier using post-matching network,” 2018 Asia-Pacific Microwave Conference (APMC) (2018) 184 (DOI: 10.23919/APMC.2018.8617227).
[7] M. Iqbal and J. Iqbal: “A 20W single-input Doherty power amplifier’s bandwidth extension for wireless communication,” 2018 15th International Bhurban Conference on Applied Sciences and Technology (IBCAST) (2018) 795 (DOI: 10.1109/IBCAST.2018.8312314).
[8] Z. Cheng, et al.: “A Doherty power amplifier with extended efficiency and bandwidth,” IEICE Electron. Express 14 (2017) 20170188 (DOI: 10.1587/elex.14.20170188).
[9] R. Giofre, et al.: “A closed-form design technique for ultra-wideband Doherty power amplifiers,” IEEE Trans. Microw. Theory Techn. 62 (2014) 3414 (DOI: 10.1109/TMTT.2014.2363851).
[10] S. Saxena, et al.: “Continuous class-EB/B power amplifier using nonlinear embedding technique,” IEEE Trans. Circuits Syst. I, Exp. Briefs 64 (2016) 837 (DOI: 10.1109/TCASII.2016.2633300).
[11] Z. Zhang and Z. Cheng: “A multi-octave power amplifier based on mixed continuous modes,” IEEE Access 7 (2019) 178201 (DOI: 10.1109/ACCESS.2019.2957926).
[12] Z. Zhang, et al.: “Design of a broadband high-efficiency hybrid class-E/BF power amplifier,” IEEE Microw. Wireless Compon. Lett. 30 (2020) 407 (DOI: 10.1109/LMWC.2020.2973487).
[13] Z. Zhang, et al.: “Efficiency-enhanced Doherty power amplifier using Chareix-like compensation technology,” Int. J. RF Microw. Comput.-Aided Eng. 29 (2019) e21949 (DOI: 10.1002/mmce.21949).
[14] M. Darwish and A.-V. Pham: “An extended symmetric Doherty power amplifier with high efficiency over a wide power range,” IEEE MTT-S International Microwave Symposium (IMS) (2017) (DOI: 10.1109/MWSYM.2017.8058794).
[15] S.Y. Zheng, et al.: “Design of ultrawideband high-efficiency extended continuous class-F power amplifier,” IEEE Trans. Ind. Electron. 65 (2018) 4661 (DOI: 10.1109/TIE.2017.2772163).
[16] R. Kalyan, et al.: “Reconfigurable and concurrent dual-band Doherty power amplifier for multiband and multistandard applications,” IEEE Trans. Microw. Theory Techn. 65 (2017) 198 (DOI: 10.1109/TMTT.2016.2614930).
[17] A.M.M. Mohamed, et al.: “Reconfigurable Doherty power amplifier for multi-frequency wireless radio systems,” IEEE Trans. Microw. Theory Techn. 61 (2013) 1588 (DOI: 10.1109/TMTT.2013.2247617).
[18] A.M.M. Mohamed, et al.: “Electronically tunable Doherty power amplifier for multi-mode multi-band base stations,” IEEE Trans. Circuits Syst. I, Reg. Papers 61 (2014) 1229 (DOI: 10.1109/TCSI.2013.2263871).
[19] W. Chen, et al.: “A concurrent dual-band uneven Doherty power amplifier with frequency-dependent input power division,” IEEE Trans. Circuits Syst. I, Reg. Papers 64 (2014) 552 (DOI: 10.1109/TCSI.2013.2268341).
[20] W. Chen, et al.: “Design and linearization of concurrent dual-band Doherty power amplifier with frequency-dependent power ranges,” IEEE Trans. Microw. Theory Techn. 59 (2011) 2537 (DOI: 10.1109/TMTT.2011.2164089).
[21] R. Kalyan, et al.: “Design strategy of concurrent multi-band Doherty power amplifier,” IET Microw. Antenna Propag. 9 (2015) 1313 (DOI: 10.1049/iet-map.2015.0033).
[22] Y. Lu, et al.: “A MEMS reconfigurable matching network for a class AB amplifier,” IEEE Microw. Wireless Compon. Lett. 13 (2003) 437 (DOI: 10.1109/LMWC.2003.818523).
[23] L.O. Chua: “Memristor: the missing circuit element,” IEEE Trans. Circuit Theory 18 (1971) 507 (DOI: 10.1109/TCT.1971.1083337).
[24] L.O. Chua and S.M. Kang: “Memristive devices and systems,” Proc. IEEE 64 (1976) 209 (DOI: 10.1109/PROC.1976.10092).
[25] L.O. Chua: “The fourth element,” Proc. IEEE 100 (2012) 1920 (DOI: 10.1109/JPROC.2012.2190814).
[26] D.B. Strukov, et al.: “The missing memristor found,” Nature 453 (2008) 80 (DOI: 10.1038/nature06932).
[27] K.D. Xu, et al.: “Two memristor SPICE models and their applications in microwave devices,” IEEE Trans. Nanotechnol. 13 (2014) 607 (DOI: 10.1109/TNANO.2014.2314126).
[28] K. Xu, et al.: “SPICE model of memristor and its application,” Proc. IEEE Intl. Midwest Symp. Circuits Syst. (2013) 53 (DOI: 10.1109/MWSCAS.2013.6674853).
[29] K. Xu, et al.: “Nano-scale memristor SPICE implementation using ideal operational amplifier model,” Proc. SPIE Int. Sym. Photoelec-
tron. Detection Imag. 8911 (2013) (DOI: 10.1117/12.2034236).
[30] Z. Zhang, et al.: “Design of a broadband high-efficiency Doherty power amplifier for 5G communication systems,” IEICE Electron.
Express 16 (2019) 20190371 (DOI: 10.1587/elex.16.20190371).