Progress In Electromagnetics Research Letters, Vol. 79, 135–141, 2018

Investigation of a Silicon-Based High Integration Reconfigurable Dipole

Han Su*, Huiyong Hu, Heming Zhang, and Yuanhao Miao

Abstract—In this paper, an on-chip high integration reconfigurable dipole with band stop filters was demonstrated. This antenna was fabricated on a high resistivity silicon wafer, and several optimized band stop filters were introduced into antenna system to replace conventional inductors and capacitors. The measured results show that the stopband of this filter can meet the requirements of the designed dipole. This method will greatly improve the integration of antenna system. On the basis of structural optimization, the proposed reconfigurable dipole realized two resonant frequencies at 1.33 GHz and 1.65 GHz, and the radiation patterns also showed satisfactory results.

1. INTRODUCTION

In recent years, the development of communication technologies becomes faster and faster. More and more researches focus on the fields of system-on-chip (SoC). SoC has many advantages over traditional antenna systems, such as lower power consumption, higher integration, and higher operating frequency. A traditional antenna system, designed on dielectric plates, has large weight, low flexibility and great bulk. Besides, the feeding network of the antenna system was designed separately, which has greatly reduced the antenna's integration [1–6]. Thus, a novel on-chip frequency reconfigurable antenna should be developed to meet the current growing requirements of communications. At present, frequency reconfigurable antennas (designed for different situations and frequency ranges) have attracted more and more attention, and their reconfigurability can be easily achieved by changing the active length of the antenna radiator. Combined with semiconductor manufacturing processes, this antenna system shows great prospects and potential, and it was more suitable for modern communications [7].

In this paper, a high integration frequency reconfigurable dipole with band stop filters was investigated. This antenna was designed on a high resistivity silicon wafer rather than FR4 or other dielectric materials, and semiconductor process was used to fabricate this antenna. The resistivity of this wafer was high (reduce the effect of dielectric on antenna's radiation characteristics) to increase the antenna gain and bandwidth. This method will greatly improve the integration of antenna system, and it makes the silicon-based reconfigurable antenna easily integrated into communication systems, such as vehicle electronic, UAV systems, smartphone chips, and IC systems [8–11]. Thus, these silicon-based miniaturized antennas have a great effect for the development of the communication systems, and this method plays an important role in guiding the research of silicon-based solid state plasma reconfigurable antennas in our future work.

In a traditional antenna system, there were several capacitors and inductors to isolate the AC signals between the antenna radiator and feeding networks. Besides, several switches (generally useing PIN diodes) were placed within the antenna system to control the active length of the antenna radiator. This method will greatly reduce the integration of antenna system, and it will become the

---

Received 17 July 2018, Accepted 11 September 2018, Scheduled 15 November 2018

* Corresponding author: Han Su (suhan@stu.xidian.edu.cn).

The authors are with the Wide Bandgap Semiconductor Technology Disciplines State Key Laboratory, School of Microelectronics, Xidian University, Xi'an 710071, China.

bottleneck of wireless communication development. Therefore, these problems promote more and more antenna systems today gradually toward miniaturization, simplification, and automation development direction [12, 13]. In this paper, an optimized band stop filter was designed to replace conventional switches, capacitors, and inductors. This filter was fabricated on silicon wafer together with the on-chip antenna, and this method further improved the integration of antenna system. The stopband frequencies of this filter were optimized to cover the dipole's operating frequencies, and the AC signals were suppressed at the end of the antenna radiator.

This paper is organized as follows. In Section 2 the working mechanism and structural parameters of the reconfigurable dipole are demonstrated. In Section 3, the design and measured results of the band stop filter are discussed. The simulation and measurement results of this high integration reconfigurable dipole are given in Section 4. Conclusion is given in Section 5.

2. STRUCTURE OF THE RECONFIGURABLE DIPOLE

The structure of the silicon-based frequency reconfigurable dipole antenna is shown in Fig. 1. The antenna was modeled as a half-wave dipole, which consisted of five parts: dipole radiator, band stop filters (A1, A2, A3, A4, A5, and A6), feeding line, silicon wafer, and ground plane. A high resistivity silicon wafer was used in the dipole design. The silicon wafer had a thickness of 450 µm, relative permittivity of 11.8, conductivity of 3 S/m, and loss tangent of 0.01. Aluminum was used for material of the dipole radiator and band stop filters with a thickness of 2 µm. In this case, the required signals were applied on dipole radiator through feeding line and suppressed by band stop filters. Through the structural optimization design, the stopband frequencies of the filters overlapped the reconfigurable dipole's operating frequencies. To obtain good S parameter, VSWR, radiation patterns, and radiation efficiency, the High Frequency Structure Simulator (HFSS) was used to optimize the structure parameters of the proposed dipole. The S_{11} and VSWR were measured by Agilent Vector Network Analyser, and the antenna's radiation performances were measured by SATIMO antenna measurement system.

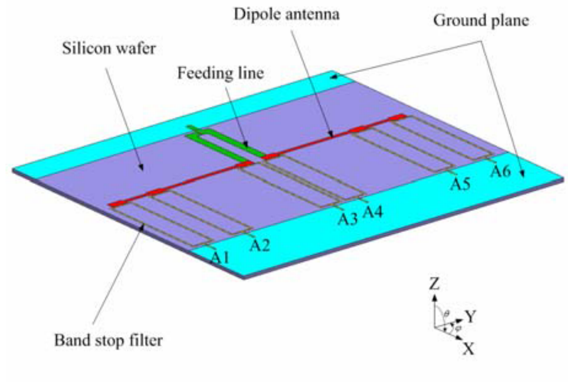


Figure 1. Structure of the reconfigurable dipole.

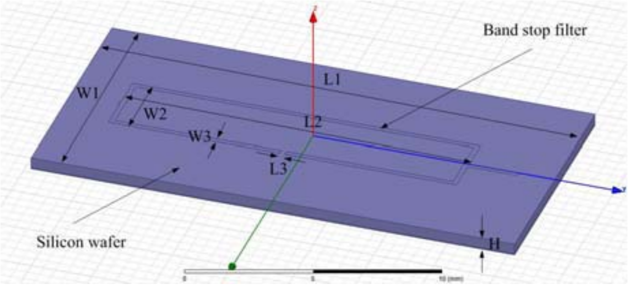


Figure 2. Structure of the optimized band stop filter.

The proposed antenna was a half-wave dipole, and its resonant frequency was controlled by the radiator's total length. Due to the existence of the band stop filters, the dipole's resonant frequency may have a little drift. In this paper, the total length of the dipole antenna was 40 mm, and it was divided into four parts by the band stop filters. Through turing on or off different band stop filters, different sections of the radiator have different current distributions, and the proposed dipole's reconfigurability was achieved. As expected, as lower radiators are turned on, the resonant frequency shifts to higher values [14–17]. Table 1 shows two configurations of the proposed dipole at different working states. There were two designed resonant frequencies when a strongly forward bias was applied on different filters. To meet the rapid development of communications, a higher frequency reconfigurable antenna can also be designed using this method. The proposed dipole in this paper was demonstrated as an example.

Table 1. Two States of the reconfigurable dipole.

Filter	A1, A6	A2, A5	A3, A4
State 1	ON	OFF	ON
State 2	OFF	ON	ON

3. BAND STOP FILTER STRUCTURE AND DISCUSSION

To replace the conventional inductors and capacitors and further improve the integration of antenna system, several band stop filters were introduced into the designed reconfigurable antenna system. These filters can pass a direct current while suppressing the required AC signals, and the stopband frequency ($S_{11} > -2\,\text{dB}$ and $S_{21} < -20\,\text{dB}$) should be optimized to cover the reconfigurable dipole's operating frequencies. In this paper, the resonant frequencies of the proposed dipole were 1.33 GHz and 1.65 GHz, respectively. Thus, the stopband of this filter should be optimized to work at the range of 1 GHz to 2 GHz.

Figure 2 shows the structure of the designed stop band filter, and its structural parameters have been optimized by HFSS. The optimized results are shown as follows: $L1 = 20\,\text{mm}$, $W1 = 10\,\text{mm}$, $H = 0.45\,\text{mm}$, $L2 = 14.4\,\text{mm}$, $W2 = 3\,\text{mm}$, $L3 = 0.2\,\text{mm}$, and $W3 = 0.2\,\text{mm}$. Through the previous optimization design, the designed stop band filter shows a good result to meet the requirements of the reconfigurable dipole.

To verify the validation of the band stop filter, this filter was fabricated and measured. Fig. 3 shows a photograph of this filter. As previously stated, this filter has good performance for the requirements. The simulated and measured S parameters of the optimized stop band filter are shown in Fig. 4, from which it can be seen that the stopband (1 GHz to 2 GHz) of this filter covers the dipole's resonant frequencies (1.33 GHz and 1.65 GHz). These results verify the usefulness of this filter, and it will greatly improve the integration of antenna system. The range of the filter's stopband is determined by its structural parameters, and it can be used in other antenna models through the structural optimization design.

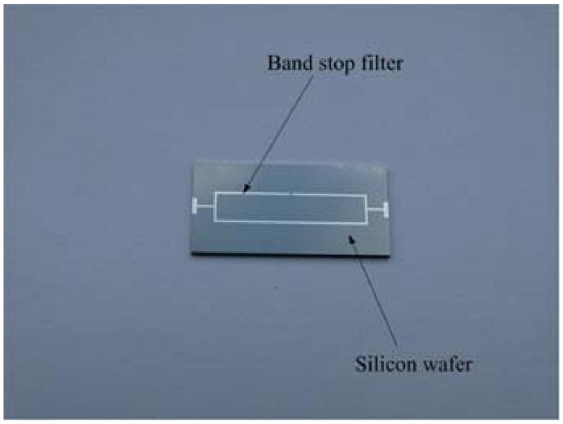


Figure 3. Photograph of the proposed band stop filter.

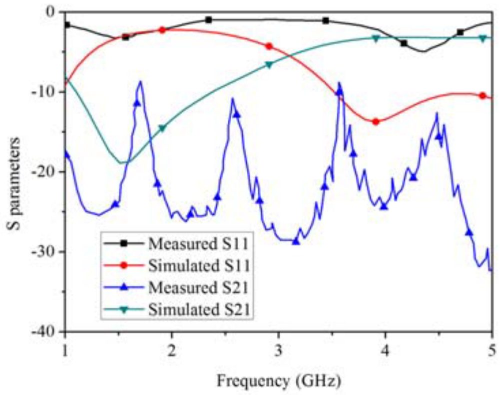


Figure 4. Measured and simulated S parameters of the proposed filter.

4. SIMULATION AND MEASUREMENT RESULTS

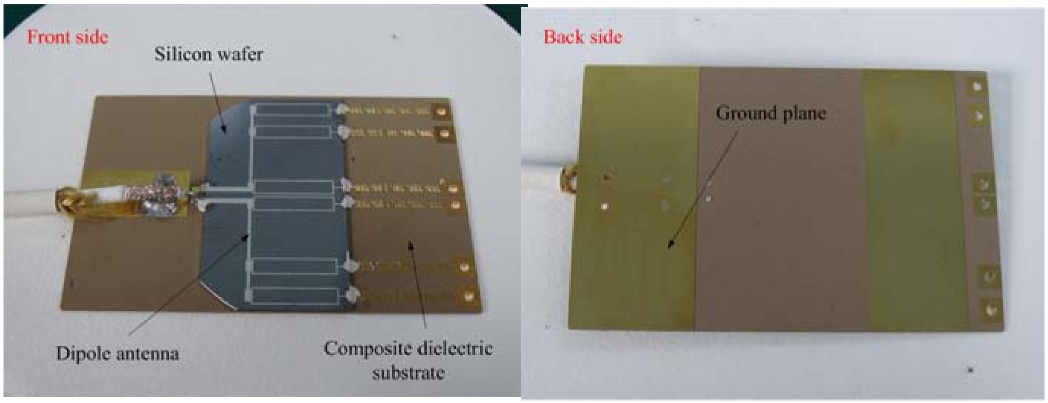
A prototype of the proposed reconfigurable dipole was fabricated, and photographs of the antenna system are shown in Fig. 5. From these photographs, we can see that the on-chip antenna system was tested on microwave composite dielectric substrate TP-2 (the relative permittivity = 9.8, the loss tangent = 1×10^{-4}, the thickness = 0.4 mm), and the measured results (S_{11}, VSWR, and radiation patterns) were obtained at room temperature.

The reflection coefficients of each working state were first tested. Fig. 6 shows the simulated and measured S_{11} of the proposed dipole, from which it can be seen that two resonant frequencies at 1.33 GHz and 1.65 GHz of this reconfigurable dipole were achieved, and each state was below −20 dB. Besides, the measurement and simulation results were well matched, and the bandwidth (below −10 dB) of the proposed dipole was about 16.3%.

Figure 7 shows the simulated and measured VSWRs of this dipole. The results indicate that the reconfigurable dipole has a good VSWR characteristic at these two configurations, and the measured VSWR can reach 1.1. Besides, measured results are in reasonable agreement with simulated ones.

The radiation patterns at 1.33 GHz and 1.65 GHz in E plane and H plane are plotted in Fig. 8. From the results, it is found that the proposed reconfigurable dipole has good broadside radiation patterns, and the disagreement between measured and simulated results may be caused by the use of silicon wafer, band stop filters, microwave composite dielectric substrate TP-2, and conductive silver paste.

The radiation characteristics depend on the current distribution and electric field distribution of dipole, and it will greatly influence the antenna's reflection coefficient and radiation patterns. Thus, it



(a) (b)

Figure 5. Photographs of the completed antenna, (a) front side of the dipole, (b) back side of the dipole.

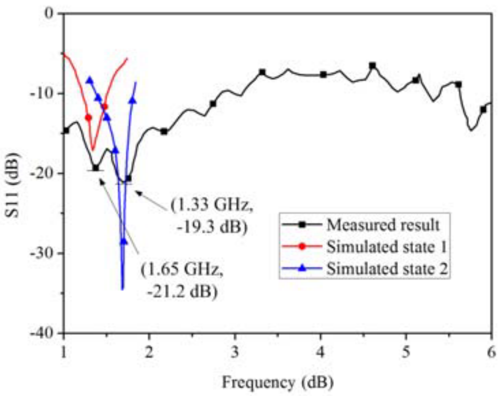


Figure 6. Simulation and measurement S_{11} of the proposed dipole.

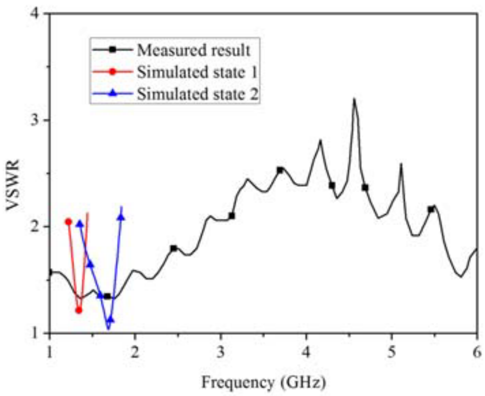
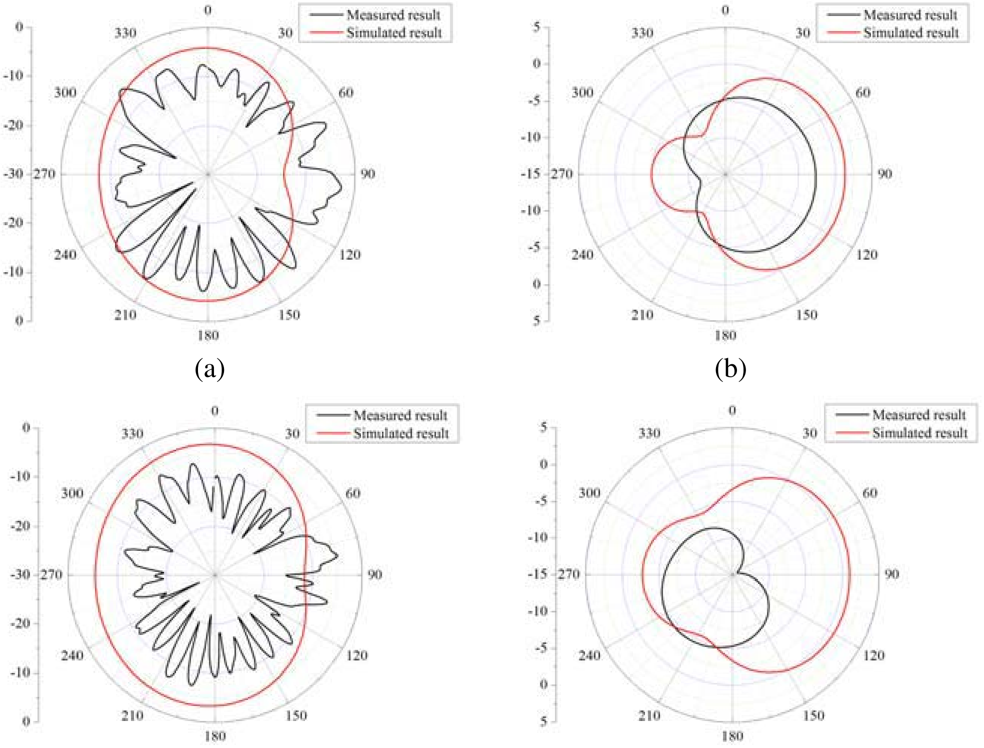


Figure 7. Simulation and measurement VSWR of the reconfigurable dipole.

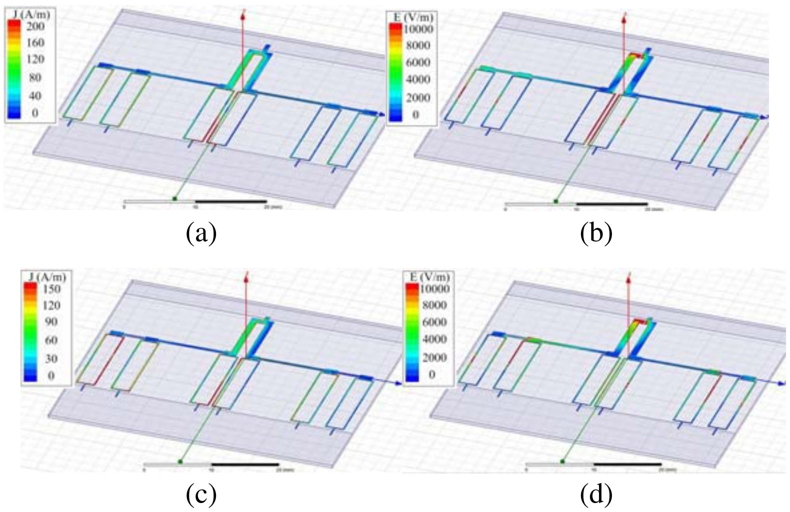
is imperative to analyze the current distributions and electric field distributions of this reconfigurable dipole. Fig. 9 shows the simulated current and electric field distributions at two configurations. The radiation efficiencies of the reconfigurable dipole at two configurations are 58.2% and 51.4%, respectively.



(a) (b)

(c) (d)

Figure 8. Simulation and measurement radiation patterns of the reconfigurable dipole, (a) E plane at 1.33 GHz, (b) H plane at 1.33 GHz, (c) E plane at 1.65 GHz, (d) H plane at 1.65 GHz.



(a) (b)

(c) (d)

Figure 9. Simulated current distributions and electric field distributions of the dipole, (a) current distributions at 1.33 GHz, (b) electric field distributions at 1.33 GHz, (c) current distributions at 1.65 GHz, (d) electric field distributions at 1.65 GHz.

5. CONCLUSION

A silicon-based high integration reconfigurable dipole was designed in this paper. This antenna was fabricated on a high resistivity silicon wafer, and the structural parameters of this reconfigurable dipole were optimized to obtain a good radiation characteristic. To replace the conventional inductors and capacitors, several optimized band stop filters were introduced into antenna system, and this method will further improve the integration of antenna system. Based on the previous results, two resonant frequencies (1.33 GHz and 1.65 GHz) of the proposed dipole were obtained, and other radiation parameters also showed good results.

ACKNOWLEDGMENT

The authors acknowledge the support from the National Natural Science Foundation of China (Grant No. 61474085), the Science Research Plan in Shaanxi Province of China (Grant No. 2016GY-085), the Opening Project of Key Laboratory of Microelectronic Devices & Integrated Technology, Institute of Microelectronics, Chinese Academy of Sciences (Grant No. 90109162905) and the Fundamental Research Funds for the Central Universities (Grant No. 20101166085).

REFERENCES

1. Han, L., C. Wang, X. Chen, and W. Zhang, "Compact frequency-reconfigurable slot antenna for wireless applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 1795–1798, 2016.
2. Valagiannopoulos, C. A., "High selectivity and controllability of a parallel-plate component with a filled rectangular ridge," *Progress In Electromagnetics Research*, Vol. 119, 497–511, 2011.
3. Row, J. S. and J. F. Tsai, "Frequency reconfigurable microstrip patch antennas with circular polarization," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 1112–1115, 2014.
4. Rajagopalan, H., J. M. Kovitz, and Y. Rahmat-Samii, "MEMS reconfigurable optimized E-shaped patch antenna design for cognitive radio," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 3, 1056–1064, Feb. 2014.
5. Genovesi, S., A. D. Candia, and A. Monorchio, "Compact and low profile frequency agile antenna for multistandard wireless communication systems," *IEEE Transactions on Antennas and Propagation*, Vol. 62, No. 3, 1019–1026, Mar. 2014.
6. Valagiannopoulos, C. A., "On examining the influence of a thin dielectric strip posed across the diameter of a penetrable radiating cylinder," *Progress In Electromagnetics Research C*, Vol. 3, 203–214, 2008.
7. Borhani, M., P. Rezaei, and A. Valizade, "Design of a reconfigurable miniaturized microstrip antenna for switchable multiband systems," *IEEE Antennas and Wireless Propagation Letters*, Vol. 15, 822–825, 2016.
8. Wang, Y., Y. Liu, H. Du, C. Liu, Q. Xue, X. Gao, S. Li, and Y. Lu, "A frequency reconfigurable microstrip antenna based on (Ba, Sr) TiO_3 substrate," *IEEE Transaction on Antennas and Propagation*, Vol. 63, No. 2, 770–775, Jan. 2015.
9. Chang, T.-N. and J.-H. Jiang, "Enhance gain and bandwidth of circularly polarized microstrip patch antenna using gap-coupled method," *Progress In Electromagnetics Research*, Vol. 96, 127–139, 2009.
10. Fikioris, G. and C. A. Valagiannopoulos, "Input admittances arising from explicit solutions to integral equations for infinite-length dipole antennas," *Progress In Electromagnetics Research*, Vol. 55, 285–306, 2005.
11. Soltani, S., P. Lotfi, and R. D. Murch, "A port and frequency reconfigurable MIMO slot antenna for WLAN applications," *IEEE Transactions on Antennas and Propagation*, Vol. 64, No. 4, 1209–1217, Apr. 2016.

12. Jusoh, M., T. Aboufoul, T. Sabapathy, A. Alomainy, and M. Kamarudin, "Pattern-reconfigurable microstrip patch antenna with multidirectional beam for WiMAX application," *IEEE Antennas and Wireless Propagation Letters*, Vol. 13, 860–863, 2014.
13. Titz, D., F. Ferrero, and C. Luxey, "Development of a millimeter-wave measurement setup and dedicated techniques to characterize the matching and radiation performance of probe-fed antennas," *IEEE Antennas Propag. Mag.*, Vol. 54, No. 4, 188–203, Aug. 2012.
14. Liu, J., Q. Xue, H. Wong, H. W. Lai, and Y. Long, "Design and analysis of a low-profile and broadband microstrip monopolar patch antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 61, No. 1, 11–18, Jan. 2013.
15. Thi Phuong Thao, H., V. Thanh Luan, and V. V. Yem, "Design of compact frequency reconfigurable planar invert-F antenna for green wireless communications," *IET Communications*, Vol. 10, No. 18, 2567–2574, Dec. 2016.
16. Geng, J.-P., J. Li, R.-H. Jin, S. Ye, X. Liang, and M. Li, "The development of curved microstrip antenna with defected ground structure," *Progress In Electromagnetics Research*, Vol. 98, 53–73, 2009.
17. Iyer, P. P., N. A. Butakov, and J. A. Schuller, "Reconfigurable semiconductor phased-array metasurfaces," *ACS Photonics*, Vol. 2, No. 8, 1077–1084, 2015.