An Ultrawideband Bidirectional Absorptive Common-Mode Filter With All-Pass Signal Transmission

Yu-Hsiang Chen and Cheng-Nan Chiu, Senior Member, IEEE
1Department of Electrical Engineering, Yuan Ze University, Taiwan

Corresponding author: Cheng-Nan Chiu (e-mail: cnchiu@saturn.yzu.edu.tw).

ABSTRACT The paper proposes a miniaturized strip-line absorptive common-mode filter using a novel and ingenious defected ground structure (DGS). The proposed filter is bidirectional and owns an ultrawide absorption band to stop common-mode noise. Its fractional bandwidth is as large as 147%. In addition, the filter allows the total transmission of differential signals up to about 15 GHz determined by the 3-dB cutoff frequency. Both the noise absorption and signal transmission bandwiths are never achieved in literatures before. An equivalent circuit model and the design principle are offered. According to these, the filter prototype with a total area of 1.1% of the square of the wavelength at the lowest frequency of the absorption band is designed and implemented. The measured results verify the design and also demonstrate the claimed performance.

INDEX TERMS Absorptive common-mode filter (A-CMF), common-mode noise, defected ground structure (DGS), differential signal, signal integrity (SI).

I. INTRODUCTION

Absorptive common-mode filters (A-CMF’s) have been published a lot in recent years [10]-[25]. The integrated passive device (IPD) process was used in [10], [11] while the typical printed circuit board (PCB) technology was applied in [12]-[25]. In comparison with the IPD process, the PCB technology has lower cost and may achieve better performance. The design of A-CMF could directly add the lumped resistors to the balanced band-pass filters [14]-[17]. The balanced filter architectures are complex for the total transmission of differential signals. Instead, it can create a broad absorption band by placing differential lines above the DGS’s which are added with lumped resistors [19]-[21]. Especially in [21], a DGS with three equal cells having a dumbbell-shaped aperture was proposed to increase the absorption bandwidth up to 104%. However, the common-mode filter is unidirectional and the transmission of differential signal can be merely up to 5.5 GHz as shown in Table 1.

In this paper, an ultrawideband bidirectional A-CMF is proposed. This filter applies the PCB strip-line technology. A new DGS is embedded into the top and bottom grounds. Few A-CMF designs used the strip-line technology till now. The major advantages of applying this technology are more compact in size and less signal distortion owing to the DGS. Therefore, the higher cut-off frequency of differential signal may achieve. Here, the differential-signal transmission can be up to 14.96 GHz. As shown in Table 1, the bandwidth of
the signal transmission is the largest in comparison with the other published filters. In addition, the newly proposed filter employs an innovative and easily-designed DGS having five cells with dumbbell-shaped apertures of three kinds. This DGS increases the absorption bandwidth to 147%. Also, the absorption bandwidth is the largest among the published filters as shown in Table 1.

The DGS can be easily designed due to that its physical mechanism is clear. The design principle and equivalent circuit model are presented. According to these, a filter prototype is designed, fabricated and measured. The agreement of measurement and simulation is well. The measured results also verify the filter performance stated above.
The differential lines k performance of the designed n. Each dielectric layer is the RO4003C simulator HFSS [26]. shown in Fig. 2. Th = d = 2.5 mm, m = 7.5 mm, p = geometric parameters of the DGS are: w = 3.55, and a loss tangent of three metal layer consider the bidirectional symmetry. the four smaller cells. Similarly, the arrangement should resistors with two different valu matching and the absorption of CM noise, four lumped impedance (DM) characteristic impedance of 100 \( \Omega \) is maintained along the whole length including the three sections. A DGS with five cells is embedded into the top and bottom planes. The five cells can be classified into three kinds as shown in Fig. 1(c). The arrangement of the five cells on each ground plane is symmetric so as to realize the bidirectional characteristic of the filter. For the impedance matching and the absorption of CM noise, four lumped resistors with two different values, R_1 and R_2, are added into the four smaller cells. Similarly, the arrangement should consider the bidirectional symmetry.

A filter prototype is designed and implemented using the PCB strip-line structure with two dielectric layers and three metal layers. Each dielectric layer is the RO4003C substrate with a thickness of 0.406 mm, a dielectric constant of 3.55, and a loss tangent of 0.0027. On the top and bottom metal layers or the ground planes, the DGS is added. The geometric parameters of the DGS are: p_1 = 2 mm, p_2 = 4 mm, p_3 = 7 mm, b_1 = 0.5 mm, b_2 = 0.55 mm, w_1 = 5.5 mm, w_2 = 7.5 mm, P = 12.5 mm, W = 21.1 mm, w_3 = w_5 = 3.5 mm, w_4 = 2.5 mm, m_1 = 3.8 mm, m_2 = 3 mm, m_3 = 0.2 mm and u_1 = u_2 = 0.8 mm. On the central metal layer, two metal strips are placed. Their related dimensions are: w_9 = 0.35 mm, w_0 = 0.3 mm, d_1 = 0.86 mm, d_2 = 0.3 mm.

The benchmark performance of the designed filter is shown in Fig. 2. The results are simulated by the full-wave simulator HFSS [26]. The differential-signal reflection and transmission, CM noise reflection and transmission, and the differential-signal group delays are shown in Fig. 2(a), (b), and (c), respectively. The differential-signal transmission could be up to about 15 GHz which is determined by the 3-dB insertion loss. In addition, the CM noise absorption band

| Refs. | Noise absorption band (GHz) | Noise absorption (FBW (%)) | Signal transmission lower cut-off frequency (GHz) | Signal transmission upper cut-off frequency (GHz) | Process/Layers | Input directions | Size( \( \lambda^2 \)) |
|-------|-----------------------------|-----------------------------|-----------------------------------------------|-----------------------------------------------|----------------|-----------------|----------------|
| This work | 2.02-13.32 | 147% | 0 | 14.96 | PCB/3 | Bidirectional | 0.011 |
| [14]  | 1.51-2.62 | 58% | 1.51 | 2.62 | PCB/2 | Bidirectional | 0.049 |
| [15]  | 2.18-4.97 | 76% | 1.38 | 5.19 | PCB/2 | Bidirectional | 0.051 |
| [16]  | 1.28-3.76 | 98% | 1.28 | 3.76 | PCB/2 | Unidirectional | 0.582 |
| [17]  | 1.2-6.7 | 139% | 0 | 12 | PCB/2 | Bidirectional | 0.026 |
| [18]  | 2.2-2.5 | 12% | 0 | 6.1 | PCB/4 | Bidirectional | 0.005 |
| [19]  | 1.8-3 | 50% | 0 | 7.4 | PCB/2 | Bidirectional | 0.140 |
| [20]  | 1.9-4.1 | 73% | 0 | 6.4 | PCB/4 | Unidirectional | 0.002 |
| [21]  | 1.7-5.45 | 104% | 0 | 5.5 | PCB/2 | Unidirectional | 0.012 |
| [22]  | 2.33-2.69 | 14% | 0 | 7.5 | PCB/2 | Unidirectional | 0.036 |

II. BIDIRECTIONAL STRIP-LINE A-CMF DESIGN

A. Filter Configuration and Its Benchmark Performance

The configuration of the proposed strip-line A-CMF is shown in Fig. 1. As shown in Fig. 1(a), the differential lines are sandwiched by a top and a bottom ground plane. The differential lines shown in Fig. 1(b) can be divided into three sections: left, center and right sections. At the center section, the distance between the two strips is intentionally reduced to make the strong coupling happen. This will improve the differential-signal transmission. Nevertheless, a differential-mode (DM) characteristic impedance of 100 \( \Omega \) is maintained along the whole length including the three sections.

A DGS with five cells is embedded into the top and bottom planes. The five cells can be classified into three kinds as shown in Fig. 1(c). The arrangement of the five cells on each ground plane is symmetric so as to realize the bidirectional characteristic of the filter. For the impedance matching and the absorption of CM noise, four lumped resistors with two different values, R_1 and R_2, are added into the four smaller cells. Similarly, the arrangement should consider the bidirectional symmetry.

A filter prototype is designed and implemented using the PCB strip-line structure with two dielectric layers and three metal layers. Each dielectric layer is the RO4003C substrate with a thickness of 0.406 mm, a dielectric constant of 3.55, and a loss tangent of 0.0027. On the top and bottom metal layers or the ground planes, the DGS is added. The geometric parameters of the DGS are: p_1 = 2 mm, p_2 = 4 mm, p_3 = 7 mm, b_1 = 0.5 mm, b_2 = 0.55 mm, w_1 = 5.5 mm, w_2 = 7.5 mm, P = 12.5 mm, W = 21.1 mm, w_3 = w_5 = 3.5 mm, w_4 = 2.5 mm, m_1 = 3.8 mm, m_2 = 3 mm, m_3 = 0.2 mm and u_1 = u_2 = 0.8 mm. On the central metal layer, two metal strips are placed. Their related dimensions are: w_9 = 0.35 mm, w_0 = 0.3 mm, d_1 = 0.86 mm, d_2 = 0.3 mm.

The benchmark performance of the designed filter is shown in Fig. 2. The results are simulated by the full-wave simulator HFSS [26]. The differential-signal reflection and transmission, CM noise reflection and transmission, and the differential-signal group delays are shown in Fig. 2(a), (b), and (c), respectively. The differential-signal transmission could be up to about 15 GHz which is determined by the 3-dB insertion loss. In addition, the CM noise absorption band

![FIGURE 3. Physical mechanism of each DGS cell. (a) The smallest DGS cell. (b) Equivalent circuit of the smallest cell. (c) The middle DGS cell. (d) Equivalent circuit of the middle cell. (e) The largest DGS cell. (f) Equivalent circuit of the largest cell.](image1)

![FIGURE 4. The current distributions on the DGS at lowest, middle and highest resonant frequencies.](image2)
should be determined by the 10-dB return loss and the 10-dB insertion loss. As shown in Fig. 2(b), the overlapped band is from 2.02 GHz to 13.32 GHz, which is equal to a fractional bandwidth (FBW) of 147%. As compared to the published A-CMF’s in Table 1, the proposed filter outperforms all the others. The differential-signal group delays fed from both directions are shown in Fig. 2(c). Again, the flatness and the equality of the delays demonstrate the bidirectional characteristic and the ultrawideband signal transmission.

B. Physical Mechanism and Design Principle

The physical mechanism of the proposed A-CMF is clear. The three kinds of DGS cells (as shown in Fig. 3(a), 3(c), and 3(e)) can generate three different resonances. Their equivalent circuits are also shown in Fig. 3(b), 3(d), and 3(f), respectively. It is essential that the center largest cell (Fig. 3(e)) should be a dual-band resonant circuit. Its entire aperture generates the lower-frequency resonance while the central ribbon-like slot creates the higher-frequency resonance.

The CM current distributions of the three cells corresponding to the first, second, and third dip in Fig. 2(b) are shown in Fig. 4. By observing these current distributions, it is obvious that the largest cell is responsible for both the lowest and highest resonant frequencies. The two smaller cells have resonant frequencies between the lowest and highest resonant frequencies. The evolution of the A-CMF may follow the steps shown in Fig. 5(a). This is from Type A to Type D. As also observed in Fig. 5(b), the filter is evolved from a dual-stopband filter to an ultrawideband stop filter. It is important to mention again that the two resonant frequencies of Type A (or the center largest cell) determine the upper and lower limits of the absorption band. Consequently, it is very convenient for quick prediction of the absorption band simply based on the largest cell.

![FIGURE 5. Evolution of the A-CMF. (a) The evolution steps. (b) The corresponding responses.](image)

![FIGURE 6. CM equivalent circuit of the proposed A-CMF](image)

![FIGURE 7. Comparison between circuit and full-wave simulations](image)

| Parameters | Value (nH) | Parameters | Value (pF) |
|------------|------------|------------|------------|
| L₁         | 1.77       | C₁         | 0.33       |
| L₂         | 2.21       | C₂         | 0.23       |
| L₃         | 0.18       | C₃         | 0.91       |
| L₄         | 3.65       | C₄         | 1.51       |
C. Equivalent Circuit

According to the above discussion, the CM equivalent circuit model of the proposed filter is resulted and presented in Fig. 6. There are five resonant circuits of three different kinds, being two single-band and one dual-band resonant circuits. Especially, the center resonant circuit has two resonant frequencies which will determine the upper limit and lower limit of the absorption band. The component values can be extracted by Q3D [27] and summarized in Table 2.

Figure 7 shows the results obtained by the equivalent circuit and the full-wave simulation. Both the results well agree with each other. Therefore, the equivalent circuit model could be applied for the initial guess of the design.

D. Geometry and Resistor Parameter Analysis

As the evolution of the filter revealed, its bandwidth highly depends on the center largest cell of the DGS. As also illustrated in Fig. 3, this cell is equivalent to a dual-band resonant circuit. Its lower and upper resonant frequencies will determine the band limits. Fig. 8 shows the study of geometry parameters of this cell as indicated in Fig. 1. The key parameters in Fig. 8(a) and (b) are, respectively, related to the variations of the lower and upper band limits.

The added resistors are majorly for the impedance matching of CM noise. After the noise entering the filter, these resistors then dissipate the energy. As shown in Fig. 9, the value of R₁ has major effect on the matching performance while the value of R₂ is applied for the finely tuning. When R₁ and R₂ are set to 40 Ohm and 90 Ohm, respectively, the bandwidth can be maximized. Here, the absorption band is from 2.02 GHz to 13.32 GHz. By comparing Fig. 8 and 9, the stop-band determined by the 10-dB insertion loss could be wider which is from 1.98 GHz to 14.53 GHz. This is due to that the CM noise could be stopped by the absorption or even the reflection mechanism. However, the reflected noise may not be favorable in some applications.
III. IMPLEMENTATION AND EXPERIMENT

A. Filter Implementation

The prototype A-CMF was fabricated as shown in Fig. 10. In order to connect the SMA connectors for measurement, the transition method [28] from a strip line to a microstrip line was applied. Then, four high-frequency SMA connectors was connected to the ports. For the better comparison, the connector effect was also considered and modeled in simulation.

B. Experimental Validation

The frequency-domain and time-domain experimental validations are shown in Fig. 11, 12 and 13. Fig. 11 displays the simulated and measured S-parameters and group delays of differential signal. Fig. 12 shows the simulated and measured S-parameters of CM noise. These figures indeed show the agreement of simulation and measurement. In addition, the bidirectional performance is confirmed again. However, the measurement does not exactly like the simulation. It is due to the non-ideal effects of materials, the fabrication uncertainties and the measurement setup. Since the frequency band of concern is extremely wide, the substrate dielectric constant and loss tangent are dispersive.
and could not be exactly modeled in simulation. In addition, many structure lines and slots are very narrow and would have dimensional uncertainties in fabrication. The measurement setup needs SMA connectors soldered with the transitions from a strip line to a microstrip line. The setup also causes unavoidable difference between measurement and simulation.

Figure 13 shows the simulated and measured eye diagrams. The digital signal has a data rate of 10 Gb/s and a rise/fall time of 20 ps. The eye diagram of a reference board is shown in Fig. 13(a). Its eye height and width are 0.99 V and 100 ps, respectively. As added with the A-CMF, the simulated eye height and width are, respectively, reduced to 0.88 V and 94.5 ps. The measured eye height and width are, respectively, reduced to 0.86 V and 97 ps. The performance is remarkable for the SI requirement.

IV. CONCLUSION

A compact bidirectional A-CMF using the PCB stripline technology and employing an innovative DGS has been proposed and studied in this paper. Its noise absorption band is ultrawide and can be up to a FBW of 147%. Its signal transmission band is from DC to 15 GHz. On the basis of the noise absorption and signal transmission bandwidths, the proposed design is the best among all the published filters. However, to more minimize the size could be a future study. The equivalent circuit model and design principle have been offered for the filter design. According to these, a filter prototype has been implemented and measured. Both the frequency-domain and time-domain results validate the design and demonstrate the practicality of the filter for modern high-speed digital applications.

REFERENCES

[1] T.-L. Wu, F. Buesink, and F. Canavero, “Overview of signal integrity and EMC design technologies on PCB: Fundamentals and latest progress,” IEEE Trans. Electromagn. Compat., vol. 55, no. 4, pp. 624–638, Aug. 2013.
[2] D. M. Hockanson, “Investigation of fundamental EMI source mechanisms driving common-mode radiation from printed circuit boards with attached cables,” IEEE Trans. Electromagn. Compat., vol. 38, no. 4, pp. 557–566, Nov. 1996.
[3] W.-T. Liu, C.-H. Tsai, T.-W. Han, and T.-L. Wu, “An embedded common-mode suppression filter for GHz differential signals using periodic defected ground plane,” IEEE Microw. Wireless Compon. Lett., vol. 18, no. 4, pp. 248–250, Apr. 2008.
[4] S.-J. Wu, H.-H. Chuang, T.-K. Wang, and T.-L. Wu, “A novel HU-shaped common-mode filter for GHz differential signals,” in Proc. IEEE Int. Electromagn. Compat. Symp., Aug. 2008, pp. 1–4.
[5] S-J Wu, C-H Tsai, T-L Wu and T. Itoh, “A novel wideband common-mode suppression filter for gigahertz differential signals using coupled patterned ground structure” IEEE Trans. Microw. Theory Techn., vol. 57, no. 4, pp. 848–855, Apr. 2009.
[6] Z. Zeng, Y. Yao, and Y. Zhuang, “A wideband common-mode suppression filter with compact-defected ground structure pattern,” IEEE Microw. Wireless Compon. Lett., vol. 57, no. 5, pp. 1277–1280, Oct. 2015.
[7] L.-H. Zhou, Y.-L. Ma, J. Shi, Jian-Xin Chen and Wenquan Che, “Differential dual-band bandpass filter with tunable lower band using embedded DGS unit for common-mode suppression” IEEE Microw. Theory Techn., vol. 63, no. 12, pp. 4183–4191, Dec. 2016.
[8] Q. Liu, “Reduction of EMI due to common-mode currents using a surface-mount EBG-based filter,” IEEE Trans. Electromagn. Compat., vol. 58, no. 5, pp. 1440–1447, Oct. 2016.
[9] C.-Y. Hsiao, C.-H. Tsai, C.-N. Chiu and T.-L. Wu, “Radiation suppression for cable-attached packages utilizing a compact embedded common-mode filter,” IEEE Trans. Compon., Packag. Manufact. Technol., vol. 2, no. 10, pp. 1696–1703, Oct. 2012.
[10] C.-Y. Hsiao, C.-H. Cheng, and T.-L. Wu, “A new broadband common-mode noise absorption circuit for high-speed differential digital systems,” IEEE Trans. Microw. Theory Techn., vol. 63, no. 6, pp. 1894–1901, Jun. 2015.
[11] C. Chan and T. Wu, “A high-performance common-mode noise absorption circuit based on phase modification technique,” IEEE Trans. Microw. Theory Techn., vol. 67, no. 11, pp. 4394–4403, Nov. 2019.
[12] L.-H. Zhou, Y.-L. Ma, J. Shi, J.-X. Chen and W. Che, “Differential dual-band bandpass filter with tunable lower band using embedded
DGS unit for common-mode suppression” IEEE Trans. Microw. Theory Techn., vol. 63, no. 12, pp. 1894–1901, Jun. 2015.

[13] P.-J. Li, Y.-C. Tseng, C.-H. Cheng, and T.-L. Wu, “A novel absorptive common-mode filter for cable radiation reduction,” IEEE Trans. Compon., Packag. Manufact. Technol., vol. 7, no. 4, pp. 511–518, Apr. 2017.

[14] W. Zhang, Y. Wu, Y. Liu, C. Yu, A. Hasan and F. M. Ghanouchi, “Planar wideband differential-mode bandpass filter with common-mode noise absorption,” IEEE Microw. Wireless Compon. Lett., vol. 27, no. 5, pp. 458–460, May. 2017.

[15] Y. Guan, Y. Wu, and M. M. Tentzeris, “A bidirectional absorptive common-mode filter based on interdigitated microstrip coupled lines for 5G ‘Green’ communications,” IEEE Access, vol. 8, pp. 20759–20769, 2020.

[16] Y. Zhu, K. Song, M. Fan, S. Guo, Y. Zhou and Y. Fan “Wideband balanced bandpass filter with common-mode noise absorption using double-sided parallel-strip Line,” IEEE Microw. Wireless Compon. Lett., vol. 30, no. 4, pp. 359–362, Apr. 2020.

[17] Y. Zhu, K. Song, M. Fan, S. Guo, Y. Zhou and Y. Fan “Common-mode noise absorption circuit using double-sided parallel-strip line,” IEEE Microw. Wireless Compon. Lett., vol. 31, no. 1, pp. 25–28, Jan. 2021.

[18] P.-J. Li and T.-L. Wu, “A novel circuit architecture of bidirectional common-mode noise absorption circuit,” IEEE Trans. Microw. Theory Techn., vol. 68, no. 4, pp. 1476–1486, Apr. 2020.

[19] C.-H. Cheng and T.-L. Wu, “Analysis and design method of a novel absorptive common-mode filter,” IEEE Trans. Microw. Theory Techn., vol. 67, no. 5, pp. 1826–1834, May 2019.

[20] P.-J. Li and T.-L. Wu, “Synthesized method of dual-band common-mode noise absorption circuits,” IEEE Trans. Microw. Theory Techn., vol. 67, no. 4, pp. 1392–1400, Apr. 2019.

[21] S.-K. Tseng, C.-N. Chiu, Y.-C. Tsao and Y.-P. Chiuou, “A Novel ultrawideband absorptive common-mode filter design using a miniaturized and resistive defected ground structure,” IEEE Trans. Microw. Theory Techn., vol. 66, no. 4, pp. 1089–1099, Apr. 2018.

[22] H.-W. Liu, C.-H. Cheng, P.-J. Li and T.-L. Wu, “A novel Compact single-stage absorption common-mode filter,” IEEE Trans. Electromagn. Compat., vol. 63, no. 1, pp. 66–73, Feb. 2021.

[23] T. Adiprabowo, D.-B. Lin, Y.-H. Zheng, Y.-H. Chen, C.-Y. Zhuang and B.-H. Tsai, “Dual-band high absorbing and broadband suppressing common-mode noise filter,” IEEE Trans. Electromagn. Compat., 2021 (in Early Access).

[24] W. T. Li, H. R. Zhang, X. J. Chai, Y. Q. Hei, J. C. Mou and X. W. Shi, “Compact dual-band balanced-to-unbalanced filtering power divider design with extended common-mode suppression bandwidth,” IEEE Microw. Wireless Compon. Lett., 2022 (in Early Access).

[25] C.-K. Chan and T.-L. Wu, “A high-performance common-mode noise absorption circuit based on phase modification technique,” IEEE Trans. Microw. Theory Techn., vol. 67, no. 4, pp. 4394–4403, Nov. 2019.

[26] ANSYS HFSS website, 2021. [Online]. Available: http://www.ansys.com/products/electronics/ansys-hfss

[27] ANSYS Q3D website, 2021. [Online]. Available: http://www.ansys.com/products/electronics/ansys-q3d-extractor

[28] T. Maleszka and G. Jaworski, “Broadband stripline to microstrip transition with constant impedance field matching section for applications in multilayer planar technologies,” In 18-th International Conference on Microwaves, Radar and Wireless Communications, 14-16 Jun., 2010.