Progress In Electromagnetics Research Letters, Vol. 97, 1–6, 2021

Microstrip Crossover on FR-4 Substrate

Takeru Inaba* and Hitoshi Hayashi

Abstract—This letter shows a compact planar microstrip crossover. The crossover design employs a microstrip to coplanar waveguide transition. The crossover is fabricated on a low cost and readily available FR-4 substrate, and simulation and measurement responses in the low frequency band have been shown. The number of GND vias forming a quasi-coaxial section that confined the electric field around the signal via was increased to improve impedance matching. The core size of the circuit is as compact as $10\,\text{mm} \times 20\,\text{mm}$ even in the low frequency band. The crossover operates in the low frequency band with insertion loss of less than 1 dB, return loss of more than 10 dB, and isolation of more than 15 dB.

1. INTRODUCTION

Microwave and millimeter-wave integrated circuits are developing rapidly and increasing in complexity. Microwave crossovers are required when transmission lines of different signals intersect. Crossovers are used, for example, when designing antenna arrays such as the Butler matrix. Therefore, recently, crossovers have become important for microwave systems.

Conventionally, a crossover was realized by using wire bonding or air bridge [1, 2]. However, these approaches require a non-planar structure, which increases fabrication costs and complexity.

Several microstrip crossover designs using planar structures have been studied. In [3], a wideband crossover design using a branch-line coupler is proposed. A wider bandwidth can be achieved by using a branch-line coupler with multiple sections. However, in the low frequency band, the circuit size becomes large. A ring structure, which is a similar planar structure, is also proposed in [4].

In [5–7], a crossover design using the microstrip to coplanar waveguide (CPW) transition is proposed. The design proposed in [7] used the quasi-coaxial section introduced in [8] to achieve a bandwidth of DC to 40 GHz.

In this letter, the design of [7] was fabricated on a low-cost and readily available FR-4 substrate, and its characteristics in the low frequency band were investigated. Unlike a crossover using a branch-line coupler, the circuit size is not large in the low frequency band, and it is compact at $10\,\text{mm} \times 20\,\text{mm}$. Furthermore, in order to investigate the influence of the quasi-coaxial section, a circuit with a different number of GND vias for forming the quasi-coaxial section was fabricated. The crossover, which increased the number of GND vias from the conventional 4 to 6, improved impedance matching. For verification, both simulated and measured performances of the designed crossover are shown.

2. DESIGN

The structure of the crossover is shown in Fig. 1. In this structure, Path 1 connecting port 1 and port 2 and path 2 connecting port 3 and port 4 intersect. Path 1 uses vias to connect to the bottom layer CPW and achieve the transition. The circuit in Fig. 1 is designed assuming a low-cost double-sided printed circuit board (FR-4 substrate). All ports are designed with $50\,\Omega$. For the substrate used, the

Received 6 January 2021, Accepted 24 February 2021, Scheduled 1 March 2021
* Corresponding author: Takeru Inaba (t-inaba-fm6@eagle.sophia.ac.jp).
The authors are with the Sophia University, Tokyo 102-8554, Japan.

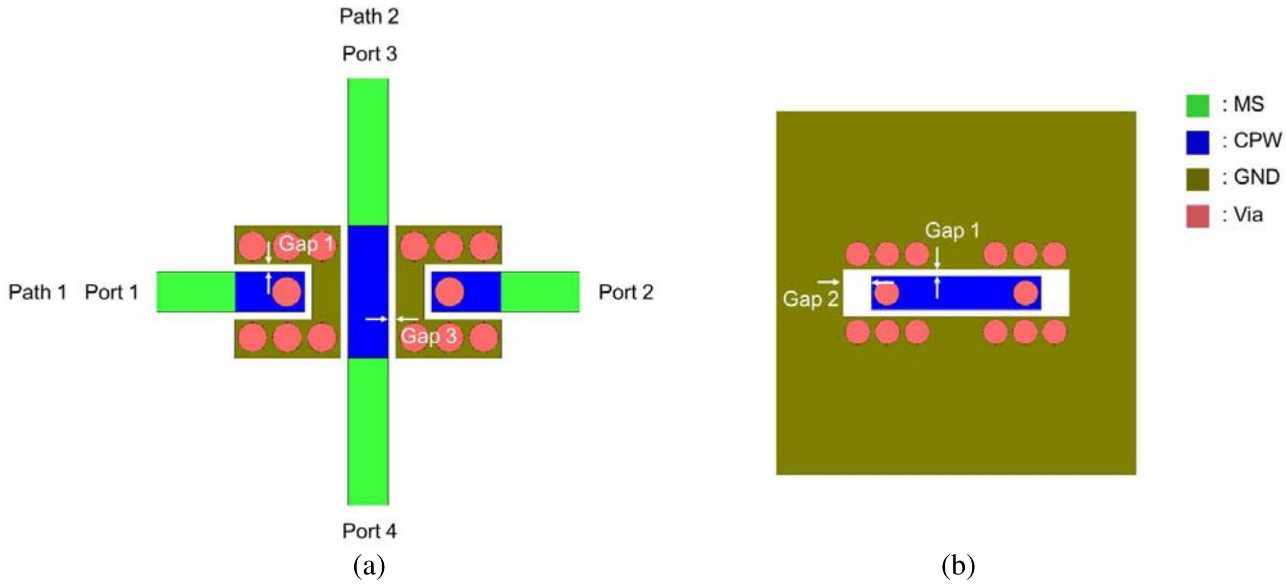


Figure 1. Crossover structure. (a) Top layer, and (b) bottom layer.

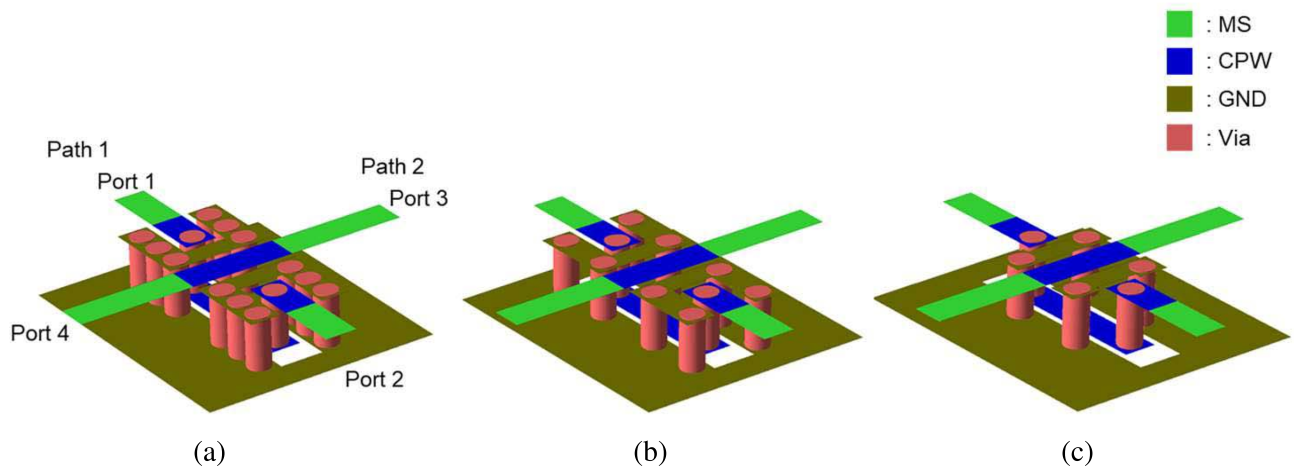


Figure 2. 3-D layout. (a) Crossover with 6 GND vias. (b) Crossover with 4 GND vias. (c) Crossover without GND section.

$50\,\Omega$ width of a Microstrip Transmission Line (MS) is 3.1 mm. The CPW line will be 3.1 mm, which is equal to the width of the MS, and the gap will be adjusted for better matching. The GND section of the top layer is responsible for implementing the CPW of the top layer.

[7] showed a circuit with 4 GND vias forming a quasi-coaxial section that confines the electric field around the signal vias. We also designed a crossover that increased the number of GND vias to 6 to improve impedance matching. Figure 2 shows a 3-D layout of a crossover with 6 GND vias, a crossover with 4 GND vias, and a crossover without GND section. Figure 3 compares the return loss of each crossover designed at a center frequency of 4 GHz. Impedance matching is better for designs with more GND vias. The crossover with 4 GND vias is 5 dB better at 2.2 GHz and 19 dB better at 5.5 GHz than a circuit without GND section. The crossover with 6 GND vias is 10 dB better at 2.2 GHz and 24 dB better at 5.5 GHz than a circuit without GND section.

For a crossover with 6 GND vias, which had the best impedance matching, when the CPW line width was fixed at 3.1 mm, the gap was adjusted to find the optimum matching. Figure 4 shows a simulated return loss when gap 1 is swept with a line width of 3.1 mm. From Figure 4, optimum impedance matching can be obtained when gap 1 is 0.6 mm. Figure 5 shows the simulated return

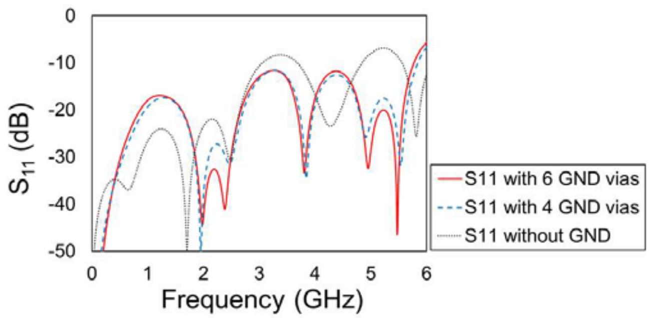


Figure 3. Simulated S_{11} for each crossover.

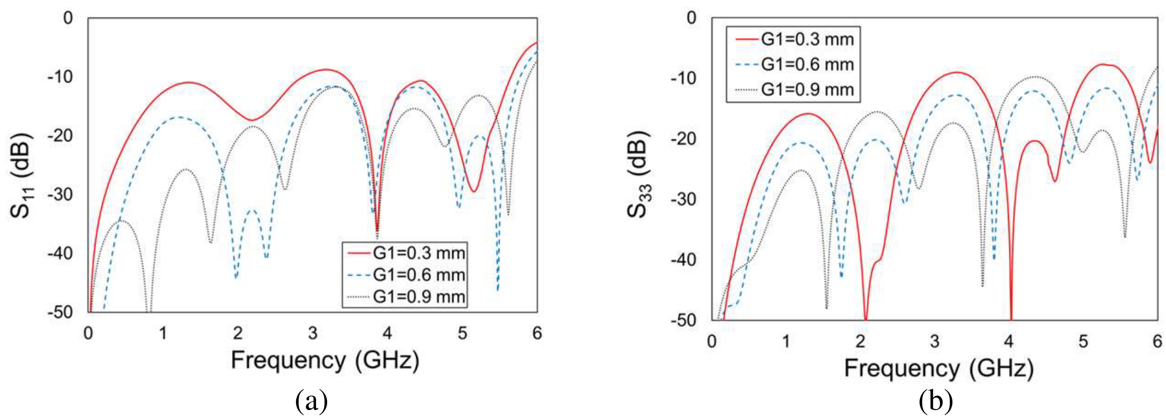


Figure 4. Return loss for different values of gap 1. (a) S_{11}, and (b) S_{33}.

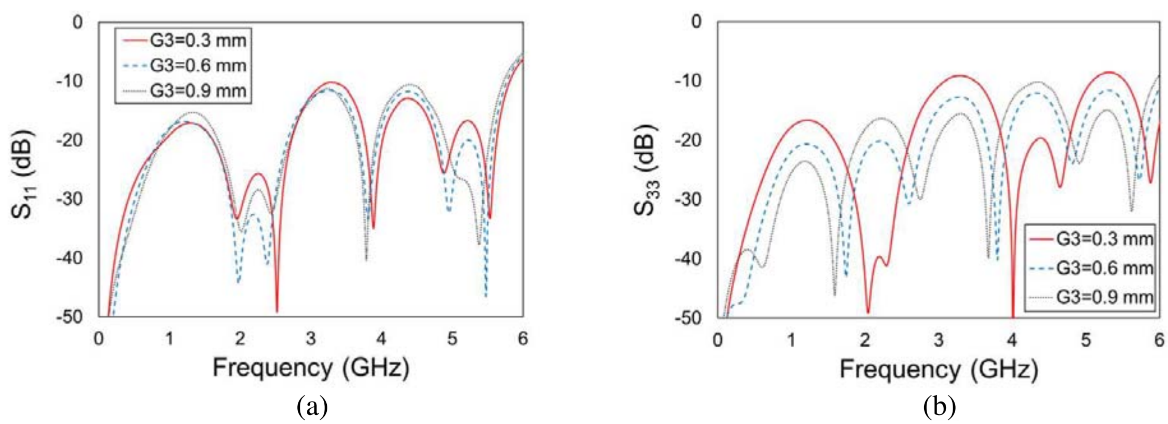


Figure 5. Return loss for different values of gap 3. (a) S_{11}, and (b) S_{33}.

loss when gap 3 is swept with a line width of 3.1 mm and gap 1 of 0.6 mm. From Figure 5, optimum impedance matching can be obtained when gap 3 is 0.6 mm. Gap 2 is 2.6 mm to match the length of the GND section of the top layer. Table 1 shows the dimensions of the designed crossover.

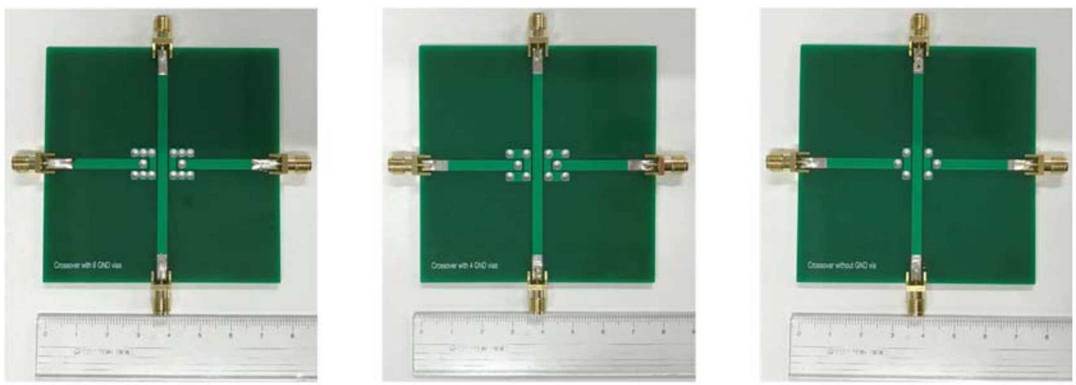
3. FABRICATION AND MEASUREMENTS

To test the design concept, we fabricated three types of crossovers with different numbers of GND vias designed at a center frequency of 4 GHz. The crossover uses a low-cost FR-4 substrate with a relative

Table 1. Dimensions of the designed crossover.

Line width	Gap 1	Gap 2	Gap 3
3.1 mm	0.6 mm	2.6 mm	0.6 mm

dielectric constant of 4.3, thickness of 1.6 mm, and $\tan\delta = 0.016$. The FR-4 substrate is a composite material and is relatively inexpensive. This substrate is not suitable for high frequency bands because the loss increases as the frequency increases. Figure 6 shows photographs of the fabricated crossovers. The overall size of the circuit is 75 mm × 75 mm, while the core size of the crossover is 10 mm × 20 mm. Figure 7 compares the measured return loss of each circuit. From the measurement results, impedance matching is improved in a design with a large number of GND vias. At 4 GHz, the return loss is 44 dB for a crossover with 6 GND vias, 31 dB for a crossover with 4 GND vias, and 13 dB for a crossover without GND section.



(a) (b) (c)

Figure 6. Fabricated crossovers. (a) Crossover with 6 GND vias. (b) Crossover with 4 GND vias. (c) Crossover without GND section.

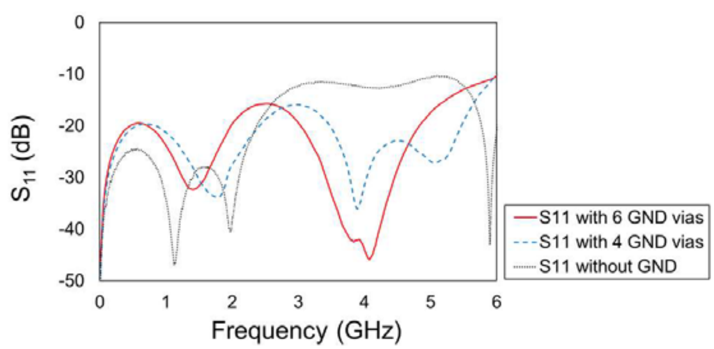
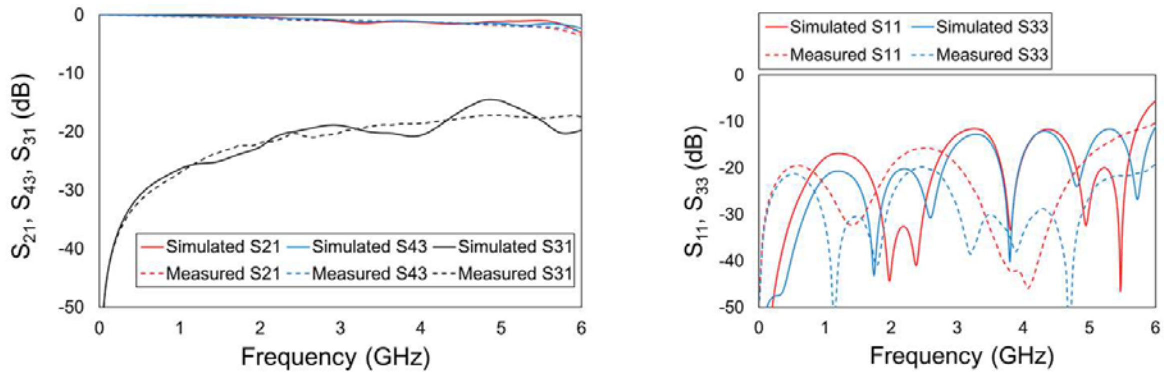


Figure 7. Measured S_{11} for each crossover.

Figure 8 compares the measured and simulated responses of a crossover with 6 GND vias. The crossover is simulated using Microwave Office's AXIEM 2.5D EM simulator. The crossover has a measured return loss of better than 10 dB and measured isolation of better than 15 dB at 10 MHz to 6 GHz. Due to the effect of extending the length of the MS to measure, measurements of insertion loss of less than 1 dB are between 10 MHz and 3.2 GHz. The difference between the measured response and simulated response results from fabrication errors and loss of SMA connectors and FR-4 substrate. Also, because the 2.5D EM simulator was used for the simulation, it is possible that accurate values could not be obtained.



(a) (b)

Figure 8. Comparison of the simulated and measured responses for the crossover with 6 GND vias. (a) Insertion loss and isolation. (b) Return loss.

Table 2 compares the proposed crossover with other designs. The proposed crossover operates at a wider band than a crossover using a branch-line coupler. Also, in the low frequency band, the proposed crossover has a compact size while the branch-line coupler has a large circuit size.

Table 2. Comparison of the proposed crossover with other designs.

Design	Bandwidth (GHz)			Size (mm)
	Return loss > 10 (dB)	Isolation > 15 (dB)	Insertion loss < 1 (dB)	
Three-section branch-line coupler [3]	1.9–3.2	2.2–2.9	2.1–3.1	61×89
Four-section branch-line coupler [3]	1.8–3.4	2.1–3.2	2.0–3.2	61×103
This work	DC-6	DC-6	DC-3.2	10×20

4. CONCLUSION

In this letter, a compact planar microstrip crossover was presented. The crossover was fabricated on a low cost and readily available FR-4 substrate and measured in the low frequency band. The crossover with 6 vias showed good impedance matching. In the low frequency band, this crossover has insertion loss of less than 1 dB, return loss of more than 10 dB, and isolation of more than 15 dB.

REFERENCES

1. Wu, S. C., H. Y. Yang, N. G. Alexopoulos, and I. Wolff, "A rigorous dispersive characterization of microstrip cross and T junctions," *IEEE Trans. Microw. Theory Tech.*, Vol. 38, No. 12, 1837–1844, Dec. 1990.
2. Horng, T.-S., "A rigorousstudy of microstrip crossovers and their possible improvements," *IEEE Trans. Microw. Theory Tech.*, Vol. 42, No. 9, 1802–1806, Sep. 1994.
3. Yao, J.-J., C. Lee, and S.-P. Yeo, "Microstrip branch-line couplers for crossover application," *IEEE Trans. Microw. Theory Tech.*, Vol. 59, No. 1, 87–92, Jan. 2011.
4. Chiou, Y. C., J. T. Kuo, and H. R. Lee, "Design of compact symmetric four-port crossover junction," *IEEE Microw. Wireless Compon. Lett.*, Vol. 19, No. 9, 545–547, Sep. 2009.

5. Liu, W., Z. Zhang, Z. Feng, and M. Iskander, "A compact wideband microstrip crossover," *IEEE Microw. Wireless Compon. Lett.*, Vol. 22, No. 5, 254–256, May 2012.
6. Abbosh, A., S. Ibrahim, and M. Karim, "Ultra-wideband crossover using microstrip-to-coplanar waveguide transitions," *IEEE Microw. Wireless Compon. Lett.*, Vol. 22, No. 10, 500–502, Oct. 2012.
7. Tajik, A., M. Fakharzadeh, and K. Mehrany, "DC to 40-GHz compact single-layer crossover," *IEEE Microw. Wireless Compon. Lett.*, Vol. 28, No. 8, 642–644, Aug. 2018.
8. Fakharzadeh, M. and S. Jafarlou, "A broadband low-loss 60 GHz die to rectangular waveguide transition," *IEEE Microw. Wireless Compon. Lett.*, Vol. 25, No. 6, 370–372, Jun. 2015.