Reply to Comments on "An Asymmetric 2.4 GHz Directional Coupler Using Electrical Balance"

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***Abstract*— The theory presented by Kumar *et al.* is based on the assumption that edge-coupled transmission lines (TLs) have infinite even-mode characteristic impedance and is clearly mentioned. Simulation is done to show that better than 10 dB matching can be achieved with a practical TL without using additional TL sections as long as impedance transformed by the even-mode of TL is much lower than the port impedance. The addition of extra quarter-wave TL sections can further improve the matching.**

***Index Terms*— Directional coupler, electrical balance, wideband isolation.**

I. Introduction

WE THANK the author for his observation and comments. The comments, made on the theory presented in [1], are based on the following assumptions regarding the transmission lines (TLs).

1) Equal phase velocity in even- and odd-mode.
2) Infinite common-mode impedance at the differential port.
3) No fringe capacitance at the open end of the TL.

The theory presented in [1] works under the assumption that the edge-coupled TLs have infinite even-mode characteristic impedance ($Z_{o,even}$) as clearly mentioned in [1, Sec. II.2].

In practice TLs have finite $Z_{o,even}$ and as explained in the comment, it should transform even-mode open-circuit of TLs at Port 4 into a short-circuit at Port 1 resulting in a complete mismatch. But unequal phase velocity in even- and odd-mode; and fringe capacitance at the open end of the TLs cause the impedance transformed by the even-mode to be much higher than port impedance. Hence in practice, there is proper matching at Port 1 without requiring extra TL sections.

Section II first illustrates the correctness of the theory for infinite $Z_{o,even}$ and then shows simulation results of practical implementation.

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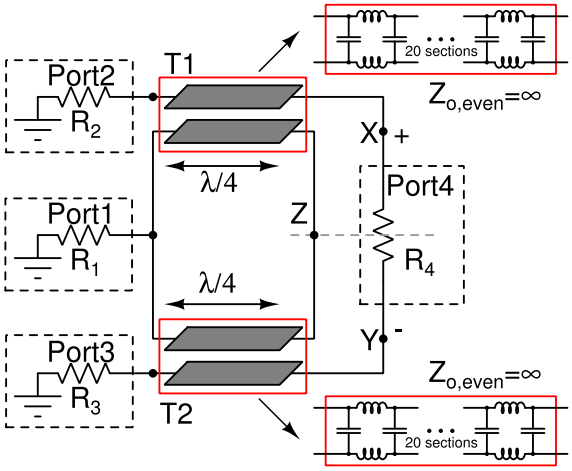

Fig. 1. Schematic of directional coupler used for simulation.

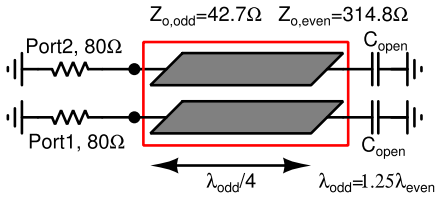

Fig. 2. Simulation set-up for a practical edge-coupled TL.

II. Simulation Results and Discussion

We simulated the directional coupler designed using TLs modeled as cascaded LC section (Fig. 1) to avoid any simulation artifacts due to distributed elements. The simulation was done using ADS 2019.1 software, and the simulated results closely match with the presented theory (ideal plots in [1, Figs. 3–6]).

To demonstrate the feasibility of the presented theory, we have set up a simulation test-bench (Fig. 2) for edge-coupled TL alone. The essential parameters of the TL have been extracted from the actual design [1]. Capacitance is added at the open-end of the TL to emulate fringe capacitance and finite common-mode impedance of the differential port (Port 4 in Fig. 1). Simulated results (Fig. 3) show that better than 10 dB matching can be maintained as long as the transformed

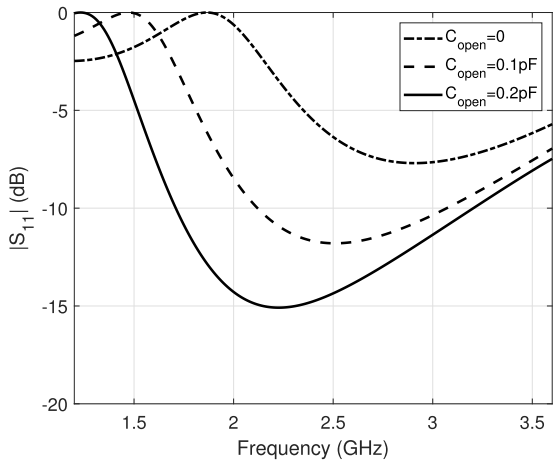

Fig. 3. Matching at Port 1 of edge-coupled TL (Fig. 2).

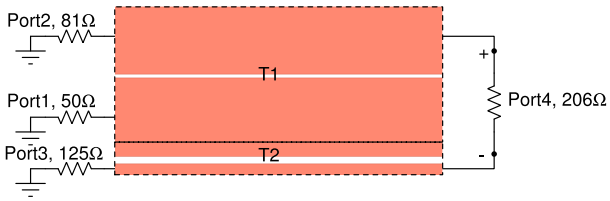

Fig. 4. Simulation set-up with layout for three-line structure. Colored regions indicate top conductor.

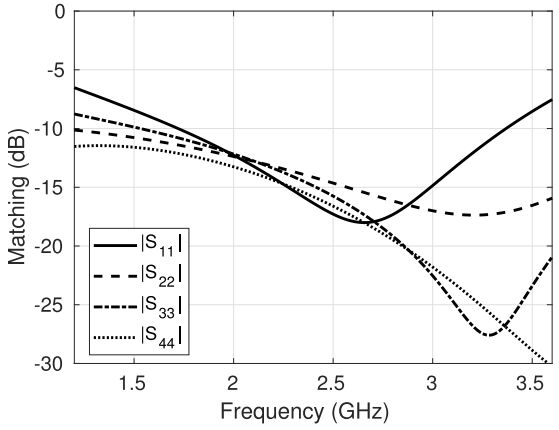

Fig. 5. Simulated matching at various ports of coupler in Fig. 4.

impedance due to even-mode of the TL is much higher than the port impedance.

Finally, just the three-line structure (Fig. 4) is simulated to validate the operation of the coupler in the absence of impedance transforming TL sections and balun. Feed lines (not shown) were added at all the ports during the simulation and later deembedded to bring the reference plane of ports to the edge of desired geometry. We borrowed the substrate parameters, physical dimensions, and port impedance values from the coupler design presented in [1].

Figs. 5–8 show simulation results of the three-line structure (Fig. 4). Matching, coupling, isolation, and coupling phase of the coupler without any other impedance transforming TL

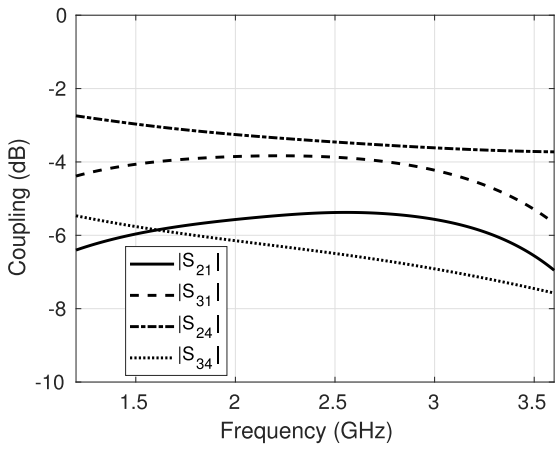

Fig. 6. Simulated coupling of coupler in Fig. 4.

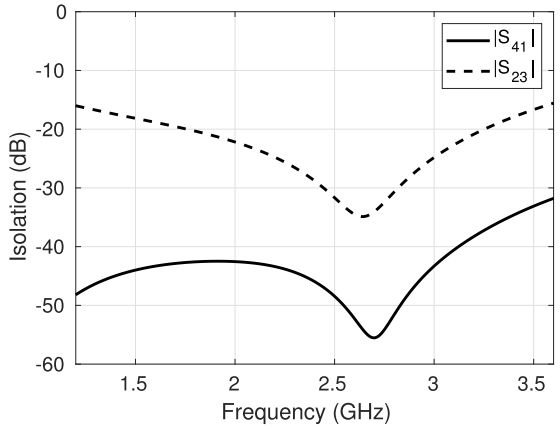

Fig. 7. Simulated isolation of coupler in Fig. 4.

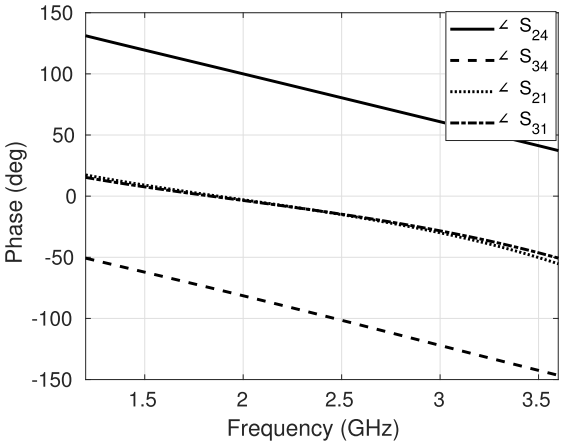

Fig. 8. Simulated coupling phase of coupler in Fig. 4.

sections and balun follow the trend as predicted by the theory presented in [1]. As mentioned in the comment, the addition of extra quarter-wave TL sections at Port 4 can further improve the matching.

REFERENCES

[1] A. Kumar, S. Aniruddhan, and R. K. Ganti, "An asymmetric 2.4 GHz directional coupler using electrical balance," *IEEE Microw. Wireless Compon. Lett.*, vol. 26, no. 12, pp. 990–992, Dec. 2016.