The implementation of wideband 90° hybrids on non-optimal substrates

Johan B. du Toit,[1,2,✉] Johan Joubert,[1] and Johann W. Odendaal[1]

[1]*Centre for Electromagnetism, University of Pretoria, Pretoria, South Africa*

[2]*Saab Grintek Defence, Centurion, South Africa*

✉Email: johan.dutoit@za.saabgroup.com

A new technique to implement wideband 90° hybrid coupling profiles on non-optimal substrate configurations is presented. The technique uses an impedance taper over the whole length of the hybrid to remove the restriction of a substrate defined maximum coupling coefficient at crossover, thus resulting in much more flexibility for the implementation of hybrids on integrated printed circuit boards. The choice of board thicknesses and material type no longer needs to be dominated by the hybrid, but can be optimized for other components or priorities. The flexibility provided by the technique is shown in the implementation of a 2–18 GHz hybrid on a large range of substrate thicknesses as well as on a non-optimal substrate material, for which acceptable measured performance is still obtained.

Introduction: Wideband microwave 3 dB, 90° hybrids are used to split signals equally between two outputs over a broad bandwidth with quadrature phasing independent of frequency. They are often also called symmetrical couplers, 90° directional couplers or quadrature couplers. Typical uses include microwave mixers, phase shifters [1], sinuous antennas [2], antenna feed networks [2], reflectometers [3] and frequency discriminators. Approximately equiripple wideband performance can be achieved by cascading multiple quarter-wavelength coupled line sections with varying coupling coefficients. Discrete coupling steps or a modified continuously variable coupling profile ($k(x)$) can be used.

Numerous synthesis techniques exist to design a coupling profile for a desired frequency response. The most commonly used types are discrete [4], piecewise discrete [5], periodic-zero based continuous [6] and quadratic spline based continuous [7]. Continuously tapered coupling profiles typically have to be used at higher frequencies to overcome the performance degradation caused by the step discontinuities. These examples are shown in Figure 1 for a 9-section, 8.343 dB, 2-18 GHz hybrid. High-performance hybrids are typically realized in offset parallel-coupled stripline [8], also called triplate, as shown in Figure 2. This transmission line is chosen because of its low dispersion and the ability to achieve high maximum coupling coefficients (k_{max}).

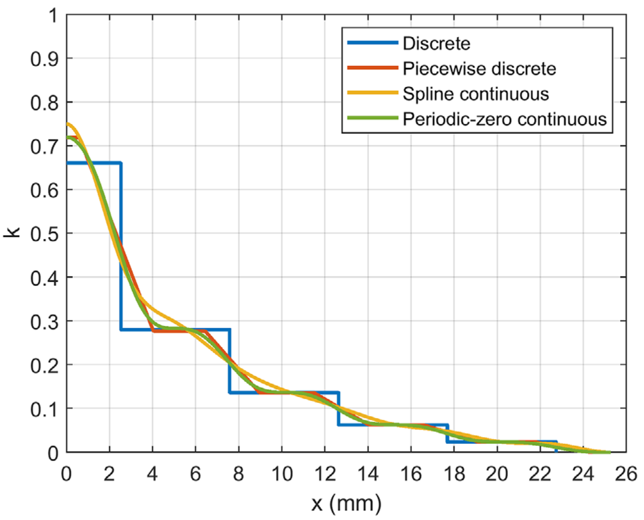

Fig. 1 *Different coupling profiles for a 2–18 GHz hybrid*

The following relation needs to be maintained for the coupled lines throughout the length of the hybrid to achieve optimal matching and isolation:

$$Z_0{}^2 = Z_{0e}(x)Z_{0o}(x), \tag{1}$$

where Z_0 is the characteristic impedance and $Z_{0e}(x)$ and $Z_{0o}(x)$ are respectively the even- and odd-mode impedances. $Z_{0e}(x)$ is related to $k(x)$ by Equation (2):

$$Z_{0e}(x) = \sqrt{\frac{1+k(x)}{1-k(x)}} \tag{2}$$

This can be achieved in a specific substrate configuration, with specific permittivity and thickness, by varying the line width (w) and offset (w_o).

In the case of a wideband 3 dB hybrid, impractically high k values are generally required to be implemented. To alleviate this requirement a tandem configuration of two 8.343 dB hybrids is used [9]. The problem with using a tandem configuration is that the two lines of the hybrid have to overlap completely. That removes a degree of freedom and a specific k_{max}, defined by the synthesized coupling profile, cannot be achieved in an arbitrary substrate configuration. The traditional solution is to choose a substrate configuration that results in Z_0 close to 50 Ω at the crossover point [10]. For example, this has led to a common periodic-zero based design [1] as shown in Figure 1, with $k_{max} = 0.7194$ implemented on Rogers RT/duroid 5880 ($\varepsilon_r = 2.2$) with a 5 mil thick centre substrate and 25 mil thick outer substrates, which results in a Z_0 at the crossover of 50.20 Ω. However, this is not always ideal as hybrids are often required in complex integrated, multi-layer printed circuit boards (PCBs), with various other active and passive components, where the choice of substrate configuration might be defined by other factors of the design. Size limitation might also force the design to consist of a specific number of sections, for which a combination of available substrate thicknesses might not be available. A technique that partially reduces this constraint is described in [11]. It uses the same optimization-based spline synthesis technique of [7], but fixes k_{max} to a desired value and a redefined spline profile to perform the optimization on. This results in some ripple in the spline, but very little performance degradation. The achievable variation in k_{max} is normally enough to change the design to the nearest available substrate thickness, but not significantly more.

Proposed design technique: A much more flexible technique is described in this paper. By introducing an integrated $Z_0(x)$ impedance taper over the length of the hybrid [1] the optimal designed k_{max} can still be used while maintaining Equation (1) over all points. The total length of the hybrid is thus not effected. This can be implemented independent of the type of coupling profile used. To illustrate this concept the periodic-zero design of Figure 1 is used, but with 50 mil instead of 25 mil thick outer substrates.

A 3D solver, in this case CST Studio Suite, is used to optimize w at the crossover to achieve the required k_{max}, and calculate the resulting $Z_{0o}(0)$. Equation (1) is then used to calculate the taper impedance at crossover. For this example $w(0) = 0.279$ mm and $Z_0(0) = 87.34$ Ω. The impedance taper from 50 Ω to $Z_0(0)$ can then be implemented over the whole length of the hybrid. A Hecken-taper [12] is used as it results in the shortest possible continuous taper, and results in a reflection coefficient of −15.02 dB at 2 GHz for this example.

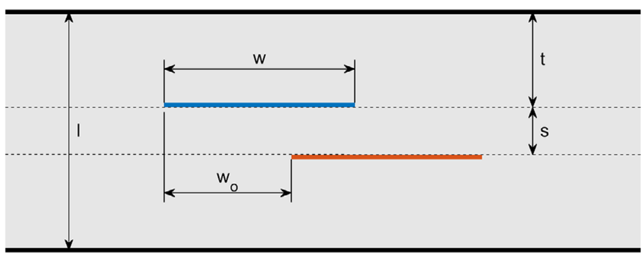

Fig. 2 *Offset parallel-coupled stripline*

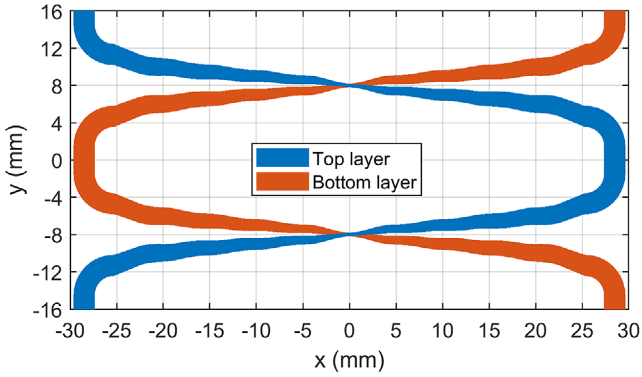

Fig. 3 *Layout of* t = *50 mil tandem design*

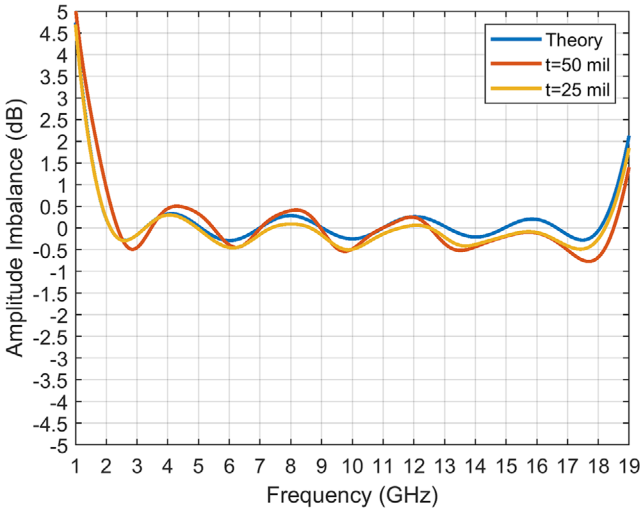

Fig. 4 *Simulated amplitude imbalance*

Once the taper has been designed, the line widths and offsets for the rest of the hybrid can be calculated by optimizing in a similar manner. $Z_0(x)$ is defined by the designed taper and $w(x)$ and $w_o(x)$ is optimized to achieve the desired $k(x)$. When the line dimensions have been calculated the hybrid implementation is complete and can be realized and simulated for the complete tandem coupler design. The final layout is shown in Figure 3 and the simulated amplitude imbalance in Figure 4 where it is compared to that of the 25 mil design as well as the theoretically analysed result, calculated as described in [7].

To show the flexibility of this technique, similar layouts were done using outer layer thicknesses ranging from 20 to 50 mil, resulting in $Z_0(0)$ values of 35.39 to 87.34 Ω at crossover. The simulated coupling results of these designs, including dielectric and conductor loss, are shown in Figure 5. The performance is good over the entire range of thicknesses and proves the high degree of flexibility provided by the technique. Any smaller or larger values result in required Z_0 values too far from 50 Ω, which in turn results in electrically short tapers and unacceptable levels of mismatch loss at the lower frequencies. In comparison, the design method described by [11] is realizable only in the limited range from 20 to 30 mil thicknesses.

Results: Apart from making it possible to use a range of substrate thicknesses, this technique can also be used to implement designs on substrates with arbitrary permittivities. This is the more typical use case when having to implement in a multi-component PCB, where the choice of substrate permittivity could be more suitably determined by other components.

As an example of such a design, it was chosen to implement and manufacture a hybrid with the same coupling profile on Rogers RO4350B ($\varepsilon_r = 3.48$), which is a material specifically designed so that it can be processed using standard epoxy/glass techniques and can thus be easily integrated with larger, complex PCBs. The chosen centre substrate thickness is 5 mil and the outer substrate thickness is 20 mil.

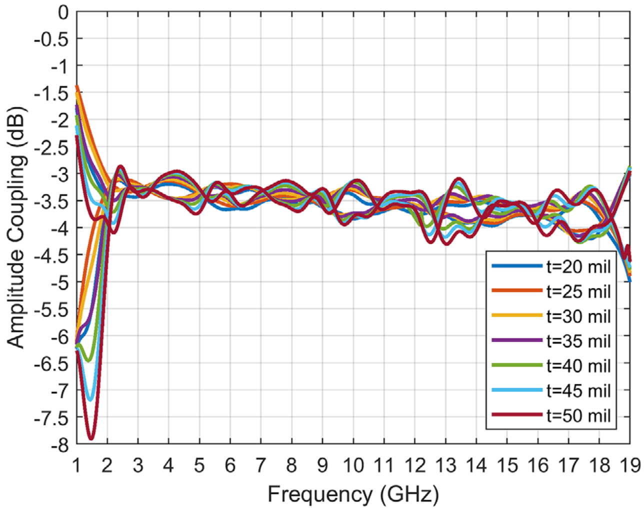

Fig. 5 *Simulated coupling for a wide range of thicknesses*

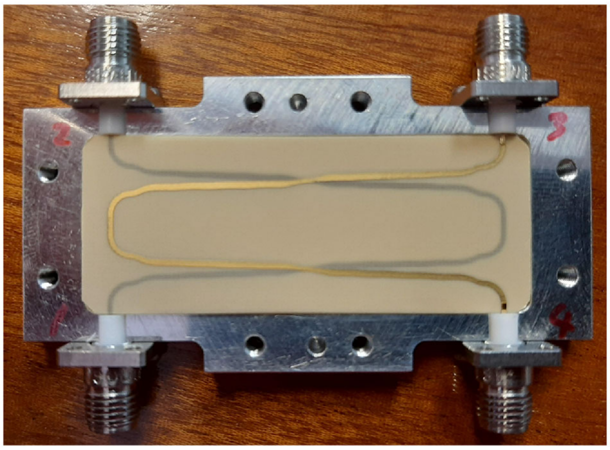

Fig. 6 *Photo of Rogers RO4350B design*

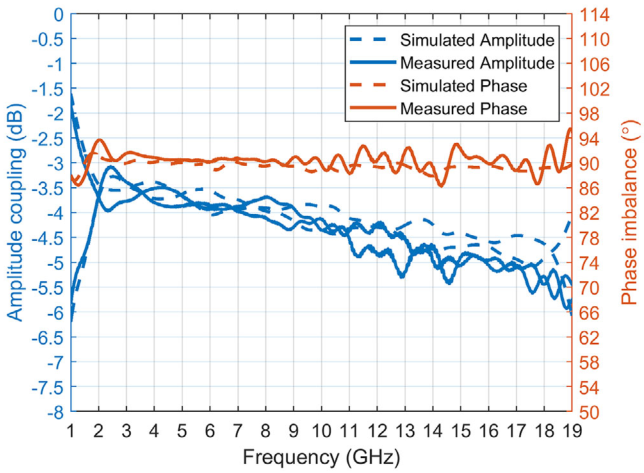

Fig. 7 *Performance of Rogers RO4350B design*

Figure 6 shows a photograph of the manufactured hybrid. The Z_0 value at crossover is 38.53 Ω and would thus not have been possible to implement successfully without the impedance taper implementation technique discussed in this paper. Figure 7 shows the measured and simulated coupling and phase imbalance performance.

As is typical, the amplitude ripple is slightly more than predicted because of very tight tolerances required, but the imbalance is still well within 1 dB. The loss is significant, mostly because of the small resulting track widths, but in an integrated PCB design as is envisaged here, it is simple to overcome. The measured phase error is very small at less than 4° across the band.

Conclusion: A design technique is presented that makes the implementation of tandem 3 dB, 90° hybrids possible on a much wider range of substrate configurations than previously possible. On complex, integrated PCB designs this means that the choice of board thicknesses and permittivity no longer needs to be dominated by the hybrid, but can be optimized for other components or priorities. It also provides more flexibility to choose the required number of sections to achieve desired amplitude ripple or possible size reduction. A range of simulations showed the degree of flexibility that is possible, and the concept was proven by implementing and testing a sample design on a non-optimal substrate that still showed good performance.

Funding information: There are no funders to report for this submission.

Data availability statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Received: *14 September 2021* Accepted: *13 October 2021*
doi: 10.1049/ell2.12355

References

1 Minnaar, F.V., Coetzee, J.C., Joubert, J.: A novel ultrawideband microwave differential phase shifter, *IEEE Trans. Microw. Theory Techn.* **45**(8), 1249–1252 (1997)
2 DuHamel, R.H.: Dual polarized sinuous antennas, US patent 4658262, (1987)
3 Lin, T., Gu, S., Lasri, T.: 2-20 GHz non-uniform coupler for six-port reflectometer, In: IEEE Topical Conference on Wireless Sensors and Sensor Networks, Phoenix, AZ, USA, 15–18 January 2017
4 Christal, E.G.: Theory and tables of optimum symmetrical TEM-mode coupled-transmission-line directional couplers, *IEEE Trans. Microw. Theory Tech.* **13**(5), 544–558 (1965)
5 Seward, S.A., Cohn, S.B.: Optimization of TEM mode tapered symmetrical couplers, *Microwave J*. **28**, 113–119 (1985)
6 Tresselt, C.P.: The design and construction of broadband, high-directivity, 90-degree couplers using nonuniform line techniques, *IEEE Trans. Microwave Theory Techn.* **14**(12), 647–656 (1966)
7 Kammler, D.W.: The design of discrete N-section and continuously tapered symmetrical microwave TEM directional couplers, *IEEE Trans. Microwave Theory Techn.* **17**(8), 577–590 (1969)
8 Shelton, J.P.: Impedances of offset parallel-coupled strip transmission lines, *IEEE Trans. Microwave Theory Techn.* **14**(1), 7–15 (1966)
9 Shelton, J.P., Mosko, J.A.: Synthesis and design of wide-band equal-ripple TEM directional couplers and fixed phase shifters, *IEEE Trans. Microwave Theory Techn.* **14**(10), 462–473 (1966)
10 Nehring, J., Hoffman, M., Munker, C.: A universal method for the design and synthesis of wideband directional couplers using non-uniform coupled transmission lines, In: Proceeding of 43rd Eurpopean Microwave Conference, Amsterdam, Netherlands, 29 October–1 November 2012
11 Millican, G.L., Wales, R.C.: Practical strip-line microwave circuit design, *IEEE Trans. Microwave Theory Techn.* **17**(9), 696–705 (1969)
12 Hecken, R.P.: A near-optimum matching section without discontinuities, *IEEE Trans. Microwave Theory Techn.* **20**(11), 734–739 (1972)