impedance of 205.24 Ω do not seem to be easy to fabricate with a microstrip technology due to a required width of approximately 40 μm for commonly used substrates (for example, for the prototype discussed in this article, the required microstrip linewidth was 42 μm for a substrate with a thickness of 20 mil and a dielectric constant of 2.2), while the physical length of the low-impedance (51.26-Ω) TLs should be reduced without a significant bandwidth compromise.

Due to the implementation difficulties, most previously reported efforts have investigated compact ring hybrids for equal power divisions and power-division ratios lower than or equal to 6 dB [49]. In [50], high power-division ratios were treated, but the size of the circuits is not compact, and the demanded power-division ratio is achieved only near the design frequency. In [51], a 12-dB power-division ratio was studied, and equivalent/artificial lumped-element TL models were suggested for high-impedance TLs. However, the extraction method for the lumped-element values seems to be very complicated, and the bandwidth is much smaller than that of the conventional one, while the size is not compact. A power-division ratio of 13 dB is investigated in Figure 30(b) [32], but the size (320.58°) is also not compact.

In [19], a novel compact wideband ring hybrid enabling the realization of arbitrarily high power-division ratios in a miniaturized form factor is introduced. In the preliminary ring design for a 12-dB power-division-ratio prototype, the circuit includes two high-impedance TLs with $Z_2 = 205.24\ \Omega$ and two low-impedance 90° TLs with $Z_1 = 51.26\ \Omega$, as mentioned previously, with each TL being as small as possible. The size-reduction approach should be different for every TL, and conventional methods (such as the T- and Π-types, as in [38] and Figure 6 with $N = 1$) cannot be applied for high-impedance TLs due to their inherent lack of a method to reduce high-impedance values to easier-to-realize lower ones.

Figure 33(b)–(d) presents various compact topologies that effectively realize the 90° and 270° electrical lengths, although their physical lengths correspond to electrical lengths much shorter than 90°. The low-impedance (Z_1) TL with an electrical length of $90°/N_T$ (N_T: arbitrary integer) in Figure 33(b) can be shortened with the MT-unit block consisting of two identical TLs with characteristic impedance of Z_T and electrical length of $\Theta_T/2$ and two identical shunt stubs with individual susceptance of $S_T/2$ in between. The 270° TL with high impedance of Z_2 in Figure 33(c) can be

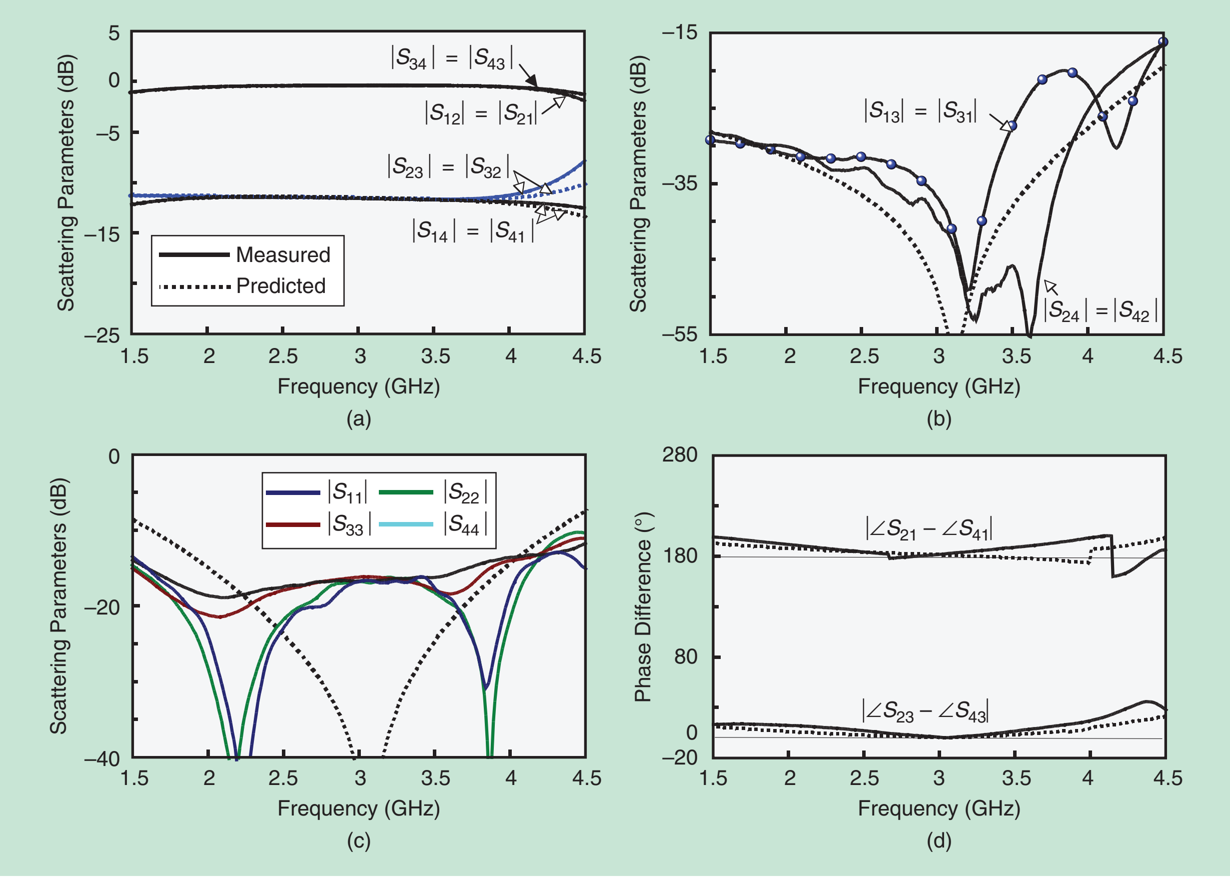

Figure 32. *The measured and simulated frequency responses for the ring hybrid with the 11-dB power-division ratio in Figure 22(b). (a) The power divisions, (b) isolations, (c) matching, and (d) phase responses.*

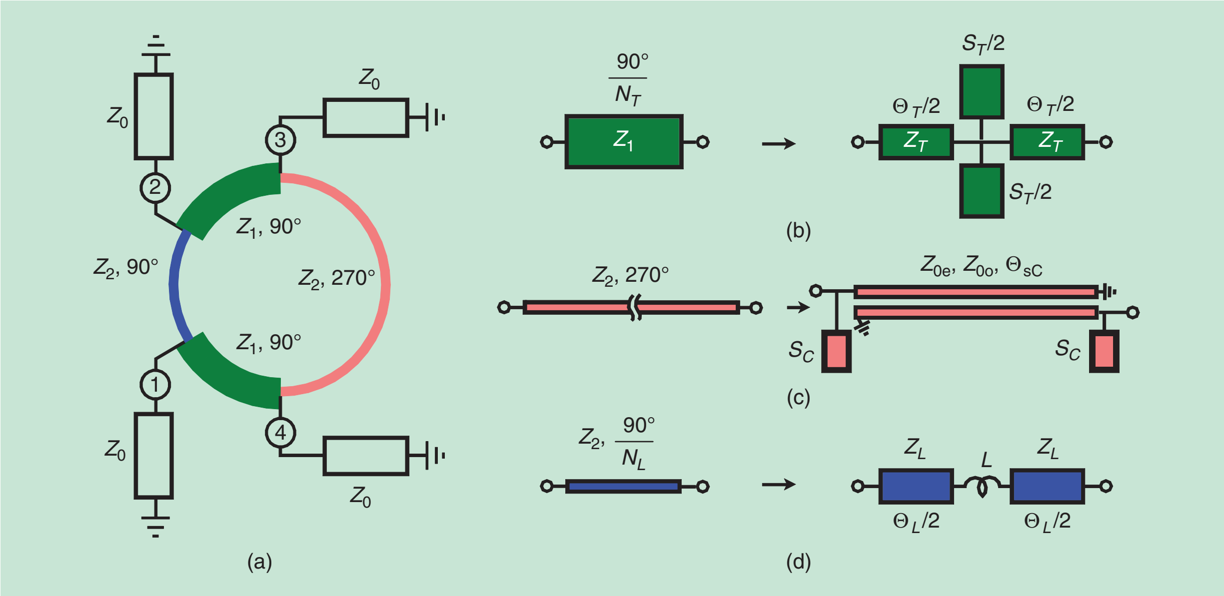

Figure 33. *A ring hybrid and its miniaturization equivalent circuits. (a) The ring hybrid. (b) The MT-unit block for a (90°/N_T) low-impedance (Z_1) TL. (c) The CΠ-section type for a 270° high-impedance (Z_2) TL. (d) The L_{S1}-unit block for a (90°/N_L) high-impedance (Z_2) TL.*

miniaturized using a CPL with even- and odd-mode impedances of Z_{0e} and Z_{0o}, electrical length of Θ_{sC}, and two-shunt open stubs. The electrical length of Θ_{sC} is much shorter than 90°, and the susceptance of each open stub is denoted as S_C. The equivalent circuit in Figure 33(c) is named the coupled-line Π-section (CΠ) type. The high-impedance (Z_2) TL with an electrical length of 90°/N_L (N_L: arbitrary integer) in Figure 33(d) can be miniaturized, with the L_{S1}-unit block composed of two identical TLs with Z_L and $\Theta_L/2$ interconnected with one series inductance, L. The integers N_T and N_L of the MT- and L_{S1}-section unit cells are typically smaller than five and represent the number of unit cells required to effectively realize the aggregate electrical lengths of 90° for the low- and high -impedance TLs, respectively.

Using the miniaturized equivalent circuits, the ring hybrid in Figure 33(a) can be reduced, and a fabricated compact CRH with a power-division ratio of 12 dB is shown in Figure 34, where low-impedance TLs are fabricated using the MT-unit block with $N = 3$ in Figure 33(b), while 270° and 90° high-impedance TLs are implemented with the CΠ-section type in Figure 33(c) and the L_{S1}-unit block with $N = 2$ in Figure 33(d), respectively.

The circumference of the fabricated prototype in Figure 34 is only 209.3° long, compared to 540° for conventional implementations, verifying an area miniaturization down to 15%, while the measured bandwidth of the 15-dB return loss is 78% versus the conventional approach's 44%, an improvement by a factor 1.8. The topology in Figure 34, introduced in [19], could be easily optimized for a wide range of power-division ratios

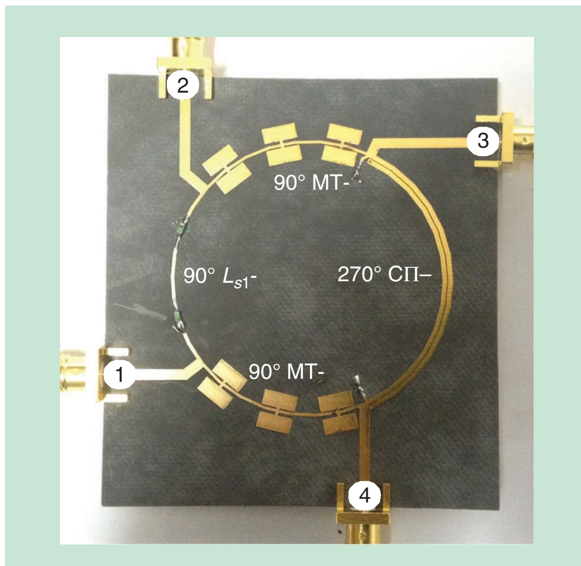

Figure 34. *The fabricated compact CRH [19].*

and set the foundation for the implementation of similar ultraminiaturized CRHs in a variety of wearable and flexible applications.

Three-Port Power Dividers and Branch-Line Hybrids With High Power-Division Ratios

The TS topologies reviewed in the previous sections can be also used for the fabrication of Wilkinson power dividers [43] and branch-line hybrids [44] with arbitrarily high power-division ratios. A typical Wilkinson power divider consists of two TLs with lengths of 90° or 270°. To achieve a 10-dB power-division ratio, one of the

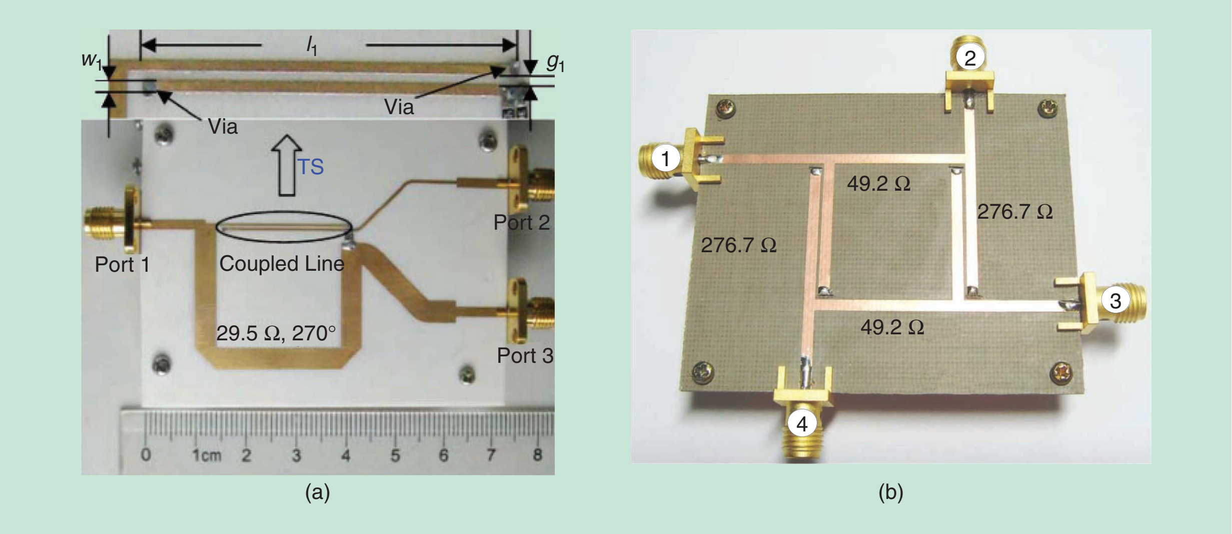

Figure 35. *The high-division-ratio power-divider prototypes using TSs. (a) The Wilkinson power divider with a power-division ratio of 10 dB [43]. (b) The branch-line hybrid with a power-division ratio of 15 dB [44].*

two TLs should feature a high impedance of 294.9 Ω, which can be implemented using one TS, as shown in the fabricated prototype in Figure 35(a).

Similarly, a typical branch-line hybrid consists of four 90° TLs or two 90° TLs and two 270° TLs. If the termination impedances are the same, the two sets of TLs located in parallel (for example, the left and right side) should be identical. To achieve a power-division ratio of 15 dB for the same termination resistance of 50 Ω, two sets of TLs with characteristic impedances of 49.2 Ω and 276.69 Ω are required. For the miniaturized fabrication of the two TLs with a 276.69-Ω characteristic impedance, the TSs can be implemented as shown in Figure 35(b).

Conclusions

This article introduced design formulas for three equivalent circuits for a directional coupler and two-port coupled line sections (TO and TS) that can be used as versatile building blocks for a variety of RF components commonly used in wearable and flexible applications. The proposed equivalent circuits for the directional coupler feature uncoupled TLs with a wide band and compact sizes; therefore, Marchand baluns can be fabricated easily in planar structures with any connecting segment. TO and TS structures can be simply realized by terminating two diagonal ports of a directional coupler in open/short circuits, and they feature unique properties compared to single TL sections, such as a miniaturized length, 180° phase shift, easy planar realization of very high characteristic-impedance values, and dc blocking.

Since design formulas for such structures have been reported in the past for only a –3-dB coupling coefficient, modified design formulas were introduced for arbitrary power coupling ratios, which enhance their applicability to applications with stringent electromagnetic interference/electromagnetic compatibility, bandwidth, and size limitations. Various examples confirming the excellent performance of the TO/TS sections were discussed. The TS-inherent 180° phase shift enables the realization of miniaturized enhanced-bandwidth ring hybrids, while the effective realization of high impedance values facilitates the design and fabrication of power dividers with arbitrarily high power division ratios, which were previously considered too difficult to realize, and sets the foundation for power dividers in wearable and flexible RF electronics.

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