

A Novel Multi-Octave Differential Power Divider

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Abstract — A novel, multi-octave differential (180°) power divider is described. The power divider circuit is based on a new kind of Magic-T circuit composed of a balun and two parallel coupled transmission lines. Results show that the proposed Magic-T circuit can achieve octave bandwidth with excellent isolation and balance. This fundamental Magic-T block is then used to create a multi-section 180° power divider capable of multi-octave performance. A 2-12 GHz, 7-section design is experimentally evaluated which exhibits excellent performance in terms of isolation, return loss, insertion loss and amplitude/phase balance.

Index Terms — hybrid coupler, magic tee, balun, coupled line circuits, Wilkinson power divider.

I. INTRODUCTION

The ability to provide multi-octave differential (180°) power division is a challenging task. Whereas in-phase power division can be accomplished using a multitude of convenient circuits [1, 2], 180° power division is generally limited to only a few options; the most popular being the narrowband rat-race coupler and the broadband asymmetric tandem coupler [3-5]. Nevertheless, few options exist which enable 180° power division over octave and multi-octave bandwidths.

Presently, the most popular method to provide multi-octave differential power division is through the use of the tandem asymmetric coupler [3-5]. The tandem asymmetric coupler is typically constructed using a tri-plate stripline geometry using Teflon based substrates. The advantages of these asymmetric tandem couplers are their decade bandwidth capability, excellent return loss and isolation and relatively good amplitude and phase balance. The major drawbacks of these designs, however, are the intrinsic impedance discontinuity in the coupled lines which degrades performance at high frequency, the necessity for tri-plate construction and the unwieldy size owing to the tandem coupled line structure. Even single octave designs are restrictively large and few, if any, of these are offered in convenient surface mount packaging. The cumbersome nature of the asymmetric tandem coupler limits its viability in broadband deployed systems, especially for applications such as balanced amplifiers and mixers where access to the in-phase port is unnecessary.

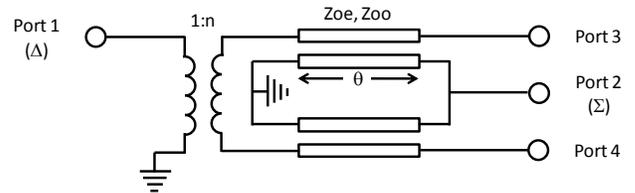


Fig. 1. Single section Magic-T structure.

To circumvent the limitations of the current technology, a new type of 180° power divider circuit is proposed. This new circuit, based on the fundamental building block of a new coupled line Magic-T, can achieve multi-octave performance using a multi-section design. Theoretical and experimental results indicate that this new power divider is well suited for octave to multi-octave bandwidth applications where good output port isolation, amplitude and phase balance are required.

II. THEORY—SINGLE SECTION DESIGN

The proposed differential power divider is based on a Magic-T circuit constructed using parallel coupled transmission lines, as shown in Fig. 1. By choosing even and odd mode impedances of the coupled lines properly, in-phase signals entering Ports 3 and 4 will be terminated in Port 2 (the Σ port) while out-of-phase signals entering Ports 3 and 4 will be terminated in Port 1 (the Δ port). In doing so, there will be isolation between Ports 1 and 2 and between Ports 3 and 4, as is required in a well-designed Magic-T.

The Δ port connects to two quarter-wave coupled line sections through a balun (as depicted by an ideal transformer). The balun performs a single ended (unbalanced) to differential (balanced) impedance transformation denoted by the transformer turn ratio $1:n$. In practice, the implementation of the balun can be accomplished using, for example, Marchand or tapered line baluns, or any other viable balun structure.

The proposed Magic-T circuit is evaluated using even/odd mode analysis as shown in Fig. 2. Here, the coupled line even mode impedance is Z_{oe} and the odd mode impedance is Z_{oo} . The differential impedance of the balun is modeled by the resistor,

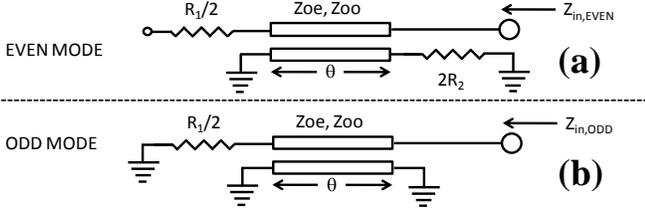


Fig. 2. Single section Magic-T decomposed into (a) even mode and (b) odd mode equivalent circuits.

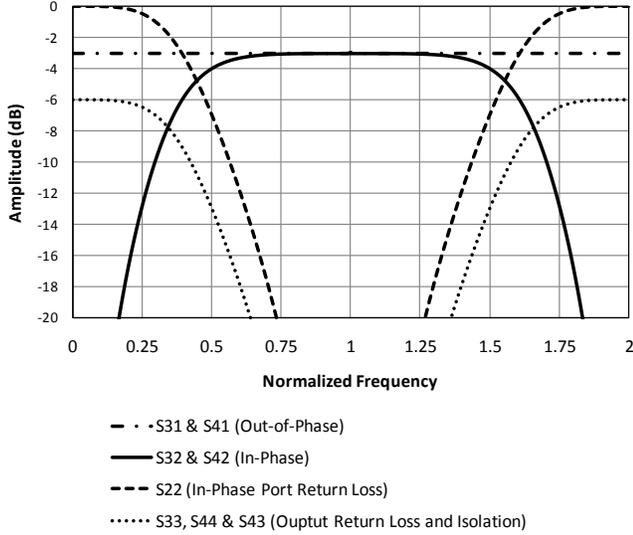


Fig. 3. Theoretical performance for the single section Magic-T. The balun is an ideal transformer with a 1 to $\sqrt{2}$ turn ratio.

R_1 and the impedance of Port 2 is modeled by resistor R_2 . For this analysis, we will assume that Port 3 and Port 4 have equal impedance, but that, in general, Ports 1 and 2 might be different. The goal, then, is to formulate design equations to calculate Z_{oe} , Z_{oo} , R_1 and R_2 in terms of the output port impedance, Z_{in} .

Due to the open circuit condition imposed on the even (in-phase) mode, resistor R_1 is open circuited. Thus, all in-phase signals will either be dissipated in the Σ port resistance or reflected. The circuit in Fig. 2a is recognized as Case #4 of the 10 canonical coupled line circuits originally identified by Jones and Bolljahn [6]. As described in [6], coupled line circuits equivalent to Fig. 2a will produce a bandpass response centered around the $\lambda/4$ frequency. For this coupled line circuit, the image impedance of the input port (i.e. Port 3) is given by

$$Z_{in} = \frac{\sqrt{Z_{oe}Z_{oo}}\sqrt{(Z_{oe}^2 - Z_{oo}^2) - (Z_{oe}^2 + Z_{oo}^2)\cos^2\theta}}{\sin\theta(Z_{oe} + Z_{oo})} \quad (1)$$

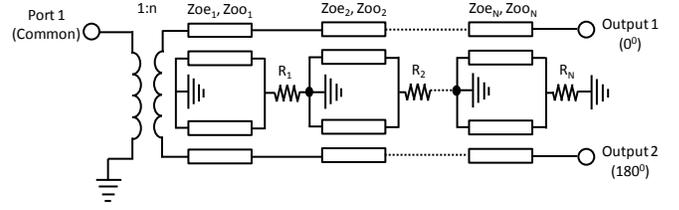


Fig. 4. Proposed multi-section differential power divider.

and the image impedance for the output port (i.e. the resistor port) is given by

$$R_2 = \frac{Z_{oe}Z_{oo}}{Z_{in}} \quad (2)$$

The odd mode case is illustrated in Fig. 2b. Here, the short circuit condition causes the elimination of R_2 demonstrating that all odd (out-of-phase) mode signals are either dissipated in the Δ port resistance or reflected. The odd mode circuit is given by Case #6 in [6]. Since Fig. 2b is recognized to have an all-pass frequency response, the bandwidth response of the Δ port is expected to be broader band than the Σ port for this Magic-T circuit. From [6], optimal match is found when

$$Z_{in} = \frac{2Z_{oe}Z_{oo}}{Z_{oe} + Z_{oo}} \quad (3)$$

and

$$Z_{in} = \frac{R_1}{2} \quad (4)$$

Design equations (1)-(4) are used to calculate Z_{oe} , Z_{oo} , R_1 and R_2 for given Port 3 and Port 4 impedance, Z_{in} . After some algebra, it can be shown that optimal impedance match is obtained when

$$c = \frac{1}{\sqrt{2}} \quad (5)$$

$$Z_c = \sqrt{2}Z_{in} \quad (6)$$

$$R_1 = 2Z_{in} \quad (7)$$

$$R_2 = Z_{in} \quad (8)$$

where coupling length, θ , is 90° and the even and odd mode impedances are re-written in terms of coupling, c , and characteristic impedance, Z_c , as

$$c = \frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}} \quad (9)$$

$$Z_c = \sqrt{Z_{oe}Z_{oo}} \quad (10)$$

TABLE I
7 SECTION POWER DIVIDER DESIGN PARAMETERS

Parameter	Section 1	Section 2	Section 3	Section 4	Section 5	Section 6	Section 7
Even Mode Impedance (Ω)	265	282	299	312	310	325	327
Odd Mode Impedance (Ω)	16.7	19.4	20.9	23.7	25.6	28.3	30.6
Intrinsic Impedance (Ω)	67	74	79	86	89	96	100
Resistor Value, Simulation (Ω)	27	20	16	10.6	6.4	1.2	1.4
Resistor Value, Experiment (Ω)	27	22	16.5	10	7.5	1	1

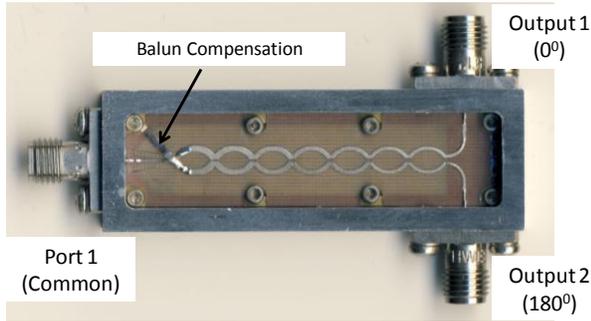


Fig. 5. Photograph of the power divider prototype. The circuit dimensions are 48.3 mm x 12.2 mm.

Therefore, in a 50Ω system, $c = 0.7071$ corresponds to a 3 dB coupler with characteristic impedance $Z_c = 70.71 \Omega$, $R_1 = 100 \Omega$ and $R_2 = 50 \Omega$. The performance of this design is shown in Fig. 3 and clearly demonstrates octave capability. As was described earlier, the Σ port response and the Δ port response differ: the Σ port shows a bandpass response while the Δ port shows an all-pass response. Of course, the Δ port will not be truly all-pass because the balun transformer will limit the achievable bandwidth (results in Fig. 3 are for an ideal balun). Nevertheless, the Δ port bandwidth response will always exceed the Σ port bandwidth as long as the balun is sufficiently broadband.

III. MULTI-SECTION DESIGN

Because its Δ port is inherently broadband, the circuit in Fig. 1 is an excellent building block to create octave and multi-octave 180° power dividers. Conveniently, the layout of the Magic-T is conducive to creating multi-section power dividers, as is depicted in Fig. 4. By replacing the Σ port of the Magic-T block with a resistor to ground, the differential power divider circuit can be made cascadable. The procedure is analogous to creating N-way Wilkinson power dividers [1]. Except for the extra area required by the balun, the multi-section 180° power divider has a circuit footprint comparable to that of a multi-section Wilkinson.

More significantly, the proposed multi-section 180° power divider will be significantly smaller than a comparable multi-octave asymmetric tandem coupler and can be potentially implemented in microstrip, stripline or suspended substrate form.

A 7-section, 2-12 GHz power divider was designed with the aid of the numerical optimization tool in Microwave Office® (Applied Wave Research Inc.). In order to satisfy the high coupling required by the coupled line sections (typical coupling was on the order of -1 to -2 dB), a broadside coupled, suspended substrate construction was used. A tapered balun was chosen at the common port owing to its broadband nature. To avoid isolation problems associated with even/odd mode dispersion, Taconic TLY-5 ($\epsilon_R = 2.2$) was chosen as the substrate material for its low dielectric constant.

A summary of the optimized 7-section design is shown in Table I. It is important to note that all circuit dimensions are easily realized using standard PCB etching techniques (trace widths ranged from 0.35 mm to 0.75 mm) and that the resistors are of reasonable values. Some resistor values were not on hand during construction and thus substitutions were made as shown in Table I. Simulations confirmed that the actual resistor values used would not change the performance of the power divider appreciably.

IV. EXPERIMENTAL RESULTS

A photograph of the constructed prototype is shown in Fig. 5. The measured results are shown in Fig. 6. Overall performance was excellent with insertion loss better than 2 dB at 12 GHz. Common Port return loss was better than 10 dB at the low end of the band and improved to 15 dB above 6 GHz. Output Port return loss was typically better than 14 dB over the entire band. Most importantly, isolation between the output ports exceeded 15 dB above about 3 GHz. Below 3 GHz, isolation degraded somewhat to 12 dB.

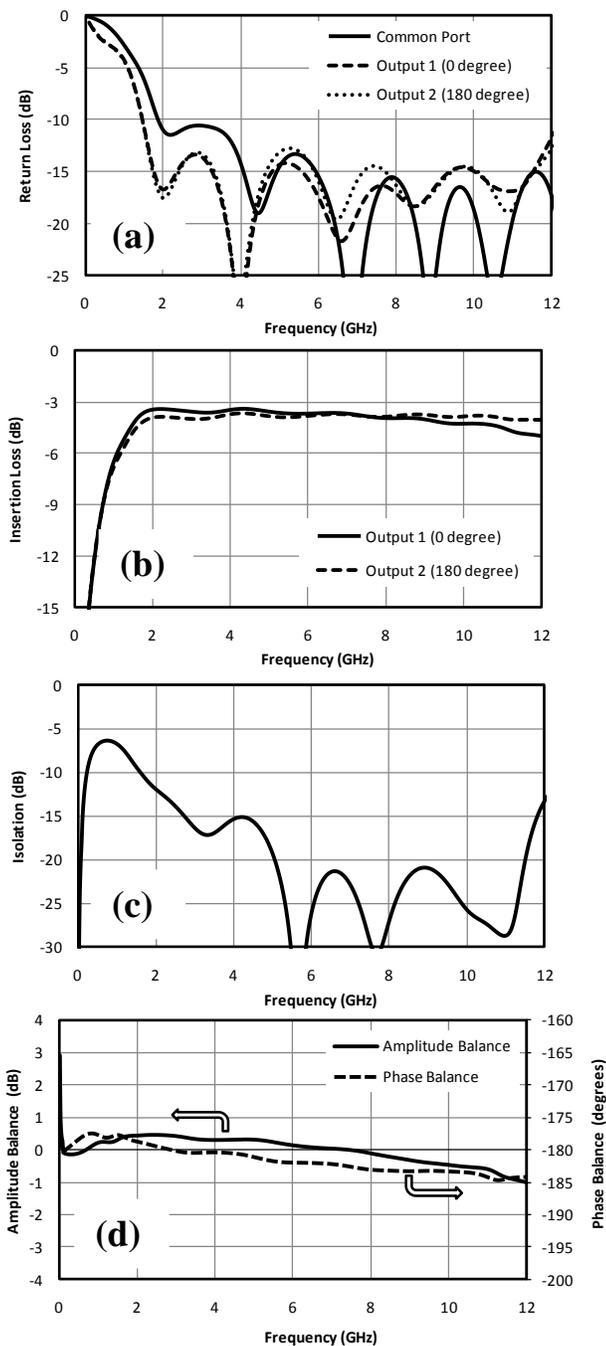


Fig. 6. Experimental results. (a) Return Loss. (b) Insertion Loss. (c) Isolation. (d) Amplitude/Phase Balance.

During the initial measurement, it was found that the power divider yielded a maximum amplitude imbalance of approximately 2 dB and a maximum phase imbalance of 30° at 2 GHz. This large circuit imbalance was caused by the uncompensated nature of the tapered balun. To remedy this, the tapered balun was compensated with a thin, 1 mm wide copper ribbon to ground (see Fig. 5). This

compensating technique is routinely used in the tuning of balanced hybrid mixers and proved extremely effective in improving the amplitude and phase balance of this 180° power divider. The only drawback to adding the balun compensation was that the common port return loss and isolation degraded a few dB near 2 GHz—this is an acceptable tradeoff considering the significant improvement in amplitude and phase balance. Overall amplitude balance was a maximum of 1 dB at 12 GHz with typical balance better than 0.5 dB. Overall phase balance was better than 6° over the entire 2 to 12 GHz band.

V. CONCLUSION

In general, few options exist that facilitate multi-octave differential power division. Although the asymmetric tandem coupler has been shown to offer extremely large bandwidth performance, these couplers are extremely large, expensive and cumbersome to use. On the other hand, the 7-section design described in this paper offers an excellent 6 to 1 bandwidth, can be built using standard suspended substrate techniques and occupies a footprint comparable to a standard multi-section Wilkinson in-phase power divider. Perhaps more importantly, the proposed design can be easily transitioned into a surface mount package using the same techniques that have already been developed for surface mountable, suspended substrate mixers. Compared to the restrictively narrowband rat-race coupler and the cumbersome asymmetric tandem coupler, the proposed differential power divider offers unique and attractive combination of traits in terms of performance, size and cost for octave and multi-octave applications.

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