A New Broadband Coupled-Line N-Way Power Combiner/Splitter

Simple interconnected coupled transmission lines provide greater bandwidth than conventional designs

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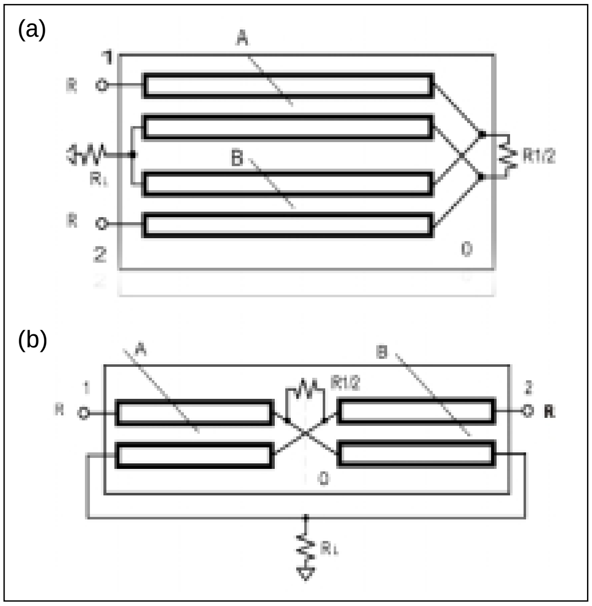
In this article, a new broadband N-way power combiner/splitter is proposed and analyzed. This coupled transmission line combiner uses two-conductor quarter-wavelength coupled lines and achieves about twice the bandwidth of previous devices within the same overall length. Multi-conductor coupled lines, as well as lumped or distributed elements, and coupled-line sections can be used to further extend the bandwidth up to a decade or more. The needed coupling coefficients are easily realizable. A significant decrease in size over conventional designs enables its realization using MEMS technology, as well as at high power.

Typically, at microwave frequencies, broadband operation requires enlarged overall device size. For example, the use of two or more sectional Wilkinson power combiners is needed if the operational bandwidth is to exceed two octaves [1, 2]. As the number of sections increases, the insertion losses and complexity of device also increase. Similarly, the increase in the number of combining amplifiers complicates overall structure, making its realization difficult for high power or MEMS technology. In an N-way and M-sectional structure, there are N × M transmission lines and N × M isolating resistors, if N > 2 (M resistors if N = 2).

In recent years, other devices have been developed that achieve significantly broader bandwidth in a reasonable size. For example, a two-way power combiner (hybrid) has been described that has a two-octave bandwidth and occupies an area of about λ/2 × λ/2 at center frequency [3].

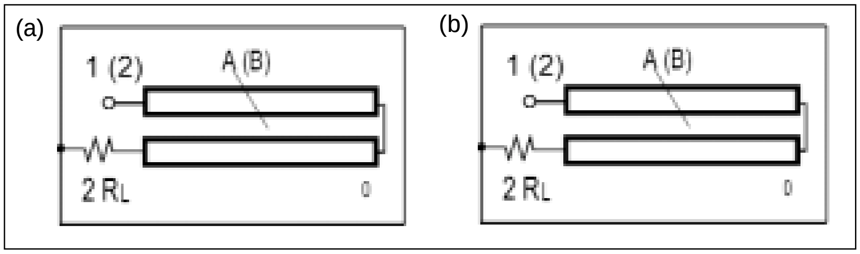
In the combiner/divider presented here, the size and insertion loss limitations are circumvented by the effective use of quarter-wavelength coupled transmission lines.



▲ **Figure 1. (a) Two-way, two-conductor coupled transmission line power combiner; (b) with vertical line of symmetry.**

Performance of simple combiners

The simplest version of the coupled transmission line two-way power combiner considered below is shown in Figure 1(a) [4]. It consists of two identical quarter-wavelength coupled transmission lines A and B, with respect to common ground 0, load resistance R_L and isolating resistor R1/2. Due to the symmetry with respect to input ports 1 and 2, it is preferable to analyze this circuit using the well-known even-odd modes approach. To make this analysis clear, redraw the circuit shown in Figure 1(a) in the form shown in Figure 1(b), which is typical for analysis of circuits with simple symmetry.



▲ **Figure 2. (a) Even-mode decomposition circuit and (b) odd-mode decomposition circuit.**

For equal magnitude and in-phase sources at ports 1 and 2, the isolating resistor R1/2 can be short-circuited. The operating circuit for each source is shown in Figure 2(a). For equal magnitude and out-of-phase sources at ports 1 and 2, the crossed conductors at the line of symmetry could be replaced by a 1:–1 ideal transformer, according to Bartlett bisection theorem [5]. The corresponding operating circuit is shown in Figure 2(b).

The first circuit, Figure 2(a), is known as a meander-line impedance transformer [6]. It defines the output reflection coefficient of combiner, or the operating in-phase reflection coefficient, at each of ports 1 and 2. For this combiner and for all that will be considered in this article, we neglect the losses in lines and assume that phase velocities are the same for all modes of propagation in the coupled transmission lines.

In the simplest case, when the transformation ratio of this meander-line transformer is equal 1:1, we have $R_L = R/2$. This is a well-known phase shifter (all-pass circuit), i.e., the even-mode reflection coefficient $\Gamma_+ = 0$. For this particular case, the bandwidth of the combiner is limited theoretically only by the isolation between ports 1 and 2, as defined by circuit Figure 2(b). The common case isolation between ports 1 and 2 is defined as

$$a_{12} = 20\log\frac{2}{|\Gamma_+ - \Gamma_-|}\ \text{dB} \qquad (1)$$

where Γ_- is the odd-mode reflection coefficient defined by circuit Figure 2(b). When $\Gamma_+ = 0$,

$$a_{12} = 20\log\frac{2}{|\Gamma_-|}\ \text{dB} \qquad (1a)$$

Condition $\Gamma_+ = 0$ will be satisfied if each coupled transmission line is symmetrical, and

$$R = \sqrt{Z_e \times Z_0} \qquad (2)$$

where Z_0 is the odd-mode characteristic impedance and Z_e is the even-mode characteristic impedance of the symmetrical coupled line [1, 2]. To minimize $|\Gamma_-|_{max}$, only one parameter (Z_0 or Z_e) could be varied, since the second one is defined by (2). For practical reason, it is important to know the correlation between Z_e, Z_0 and coupling coefficient of lines [1, 2].

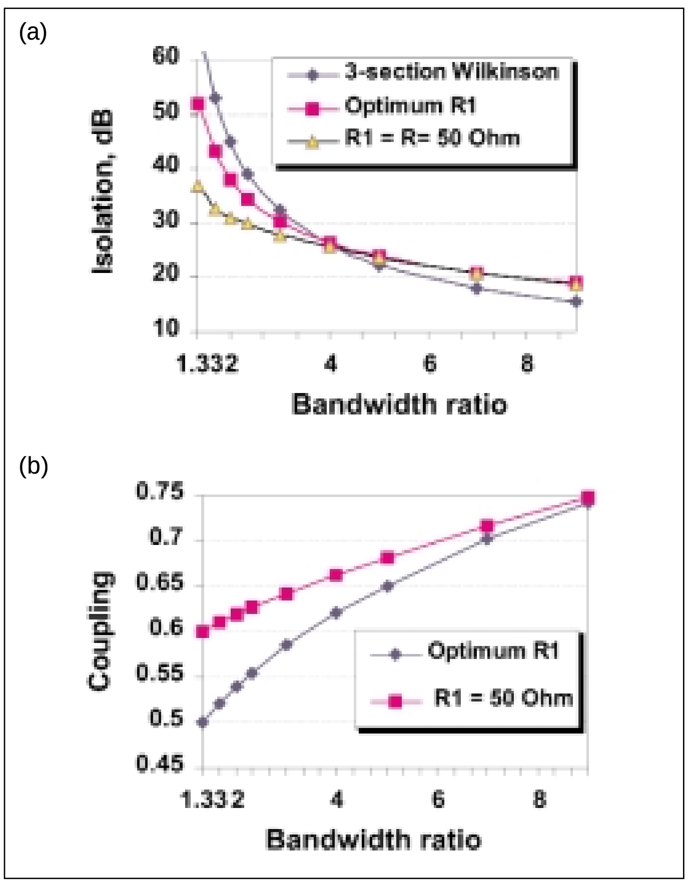
$$k = \frac{Z_e - Z_0}{Z_e + Z_0} \qquad (3)$$

Using Equation (2), we find

$$k = \frac{Z_e^2 - R^2}{Z_e^2 + R^2} = \frac{R^2 - Z_0^2}{R^2 + Z_0^2} \qquad (4a)$$

or

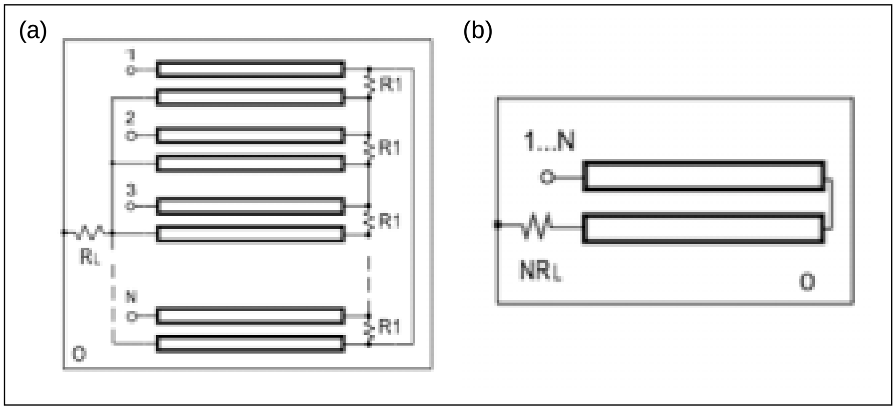
$$Z_e = R\sqrt{\frac{1+k}{1-k}},\ Z_0 = R\sqrt{\frac{1-k}{1+k}} \qquad (4b)$$



▲ **Figure 3. Optimized characteristics of a two-way combiner; (a) isolation; (b) coupling.**

The second variable parameter is the value of isolating resistor R1.

For the circuit shown in Figure 1(a), which should satisfy Equation (2), the optimum values of R1 and of



▲ **Figure 4. (a) Single-section N-way combiner with two-conductor coupled lines; (b) in-phase decomposition circuit.**

the line impedances for any given bandwidth ratio, $\alpha = f_{max}/f_{min}$, can be obtained numerically and analytically as well. Since numerical solutions are simpler for more complex circuits, only results of numerical solutions will be presented. The software GENESYS Version 6.5 from Eagleware Corporation has been used as a suitable tool for optimization of such circuits.

The procedure of characteristics calculation for all considered combiners includes the first step, in-phase (or output) VSWR minimization, and the second step, isolation maximization, using constraints on line parameters defined in the first step and freedom in the isolating elements.

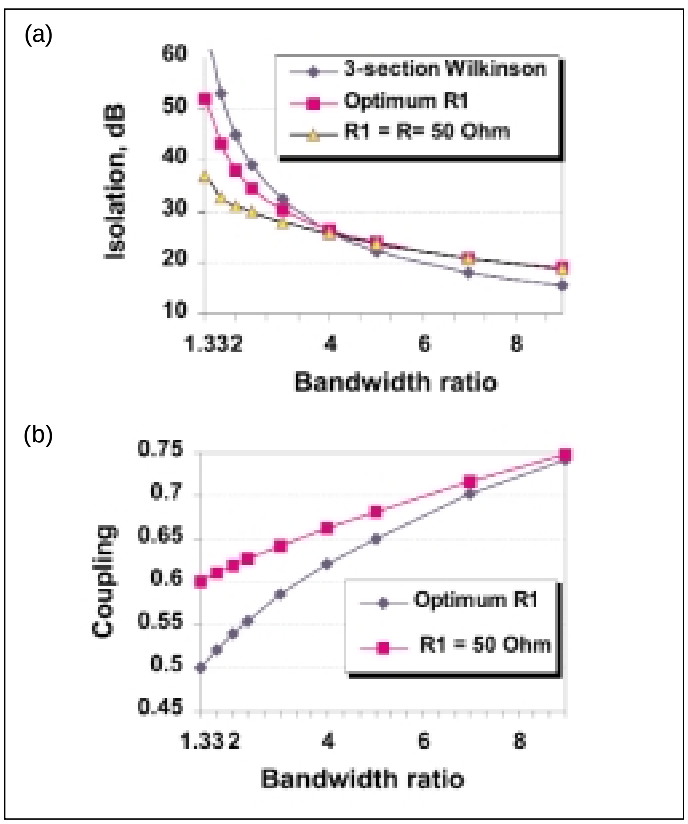
The results of optimization for circuit Figure 1 when $R = 2R_L$ = 50 ohms are shown in Figure 3. These curves show that for bandwidth ratios above four, where the isolation becomes critical, the new combiner (a structure about one third the size of a three-section Wilkinson) achieves better performance. At a bandwidth ratio below four, there is non-significant penalty in isolation, but this is high in any case.

The basic Figure 1(a) design can be extended to an N-way combiner in a straightforward way. An N-way combiner with identical two-conductor coupled lines is shown in Figure 4(a). In the particular case of Figure 1(a), two resistors R1 are connected in parallel and shown as R1/2

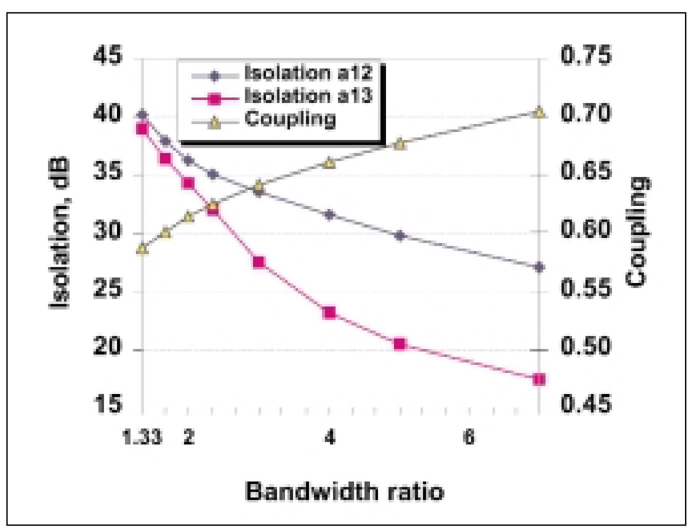
The in-phase mode decomposition circuit shown in Figure 4(a) corresponds to Figure 2(a) for N = 2. Decomposition circuits for N – 1 modes analogous to the odd-mode for N = 2 also exist. They correlate to Figure 2(b) but are not presented, due to the necessity of specific explanation away from the aim of this article, and because they are not used directly in numerical optimization.

The optimized characteristics of a single-section, three-way combiner for the particular case $R_L = R/3$ (typically R = 50 ohms) are shown in Figure 5. Similar results of optimization for a four-way combiner are shown in Figure 6.

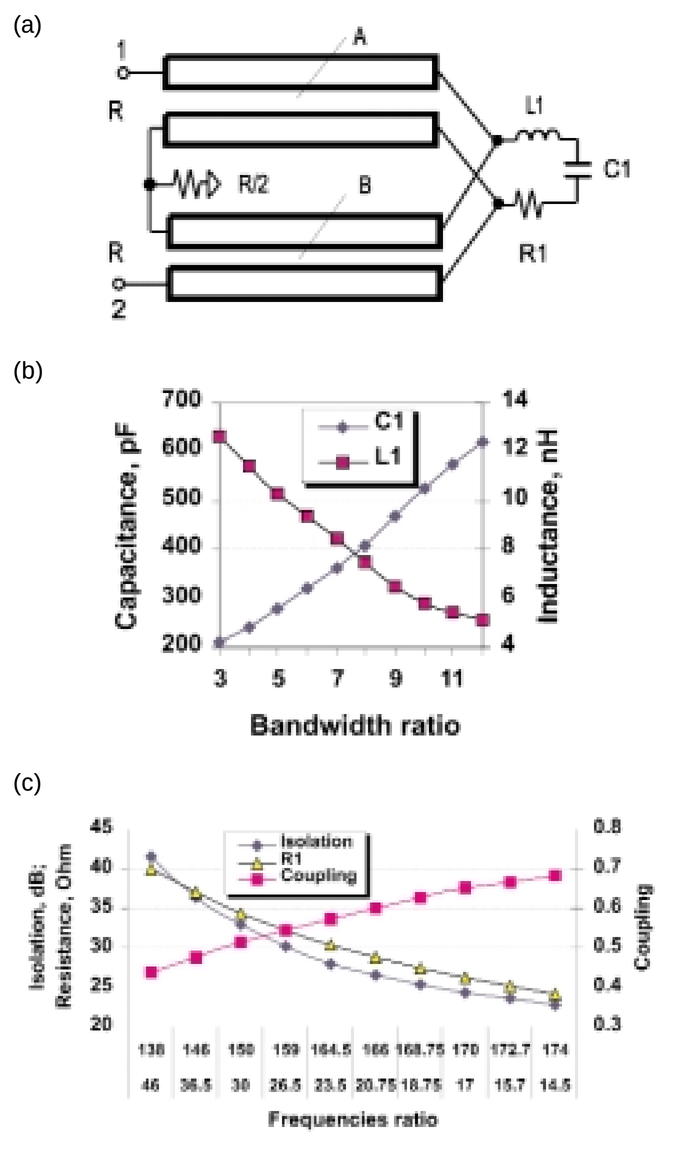
In both cases (N = 3 and N = 4), only a small effect in isolation will be seen using non-standard isolating



▲ **Figure 5. (a) Characteristics of isolation ($a_{12} = a_{23} = a_{13}$) for a three-way combiner and (b) the corresponding coupling coefficient.**



▲ **Figure 6. Characteristics of isolation ($a_{12} = a_{23} = a_{34} = a_{41}$; $a_{13} = a_{24}$) and coupling coefficient for a single-section four-way combiner with $R_L = R/4$ and R1 = R.**



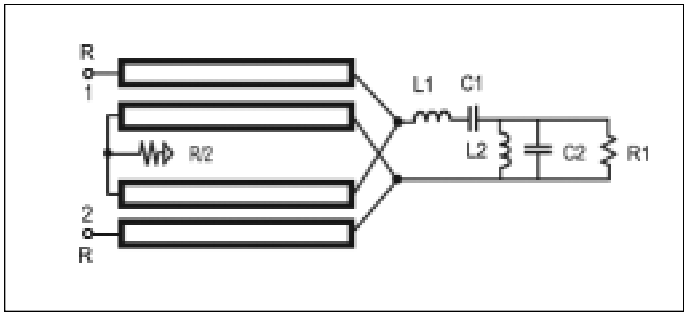
▲ **Figure 7. Two-way combiner with (a) series LC-correction; (b) LC values; (c) characteristics.**

resistors when R1 ≠ R, assuming typical impedance at inputs R = 50 ohm. The optimum value of R1 is varied with bandwidth ratio.

In most practical cases, it is preferable to have impedances at all ports (inputs and output) to be equal. This means that the power combiner should affect an internal impedance transformation. The price for this additional property is narrowed bandwidth, which is true for the Wilkinson design and others.

Simple combiners with correction

Simple correction networks effectively provide extended operating bandwidth [7]. In particular, a series LC-circuit may be connected with isolating resistors. This type of correction can be used also for increasing the isolation between inputs of an N-way combiner. An example of a two-way combiner with this LC-correction is shown in Figure 7. In this example, R = 50 ohms, and the electrical length of symmetrical coupled transmission line (for even and odd modes) equals 90 degrees at a central frequency of f_0 = 100 MHz. The values of elements L1, C1 and R1 for any central frequency f_0 and R could be calculated using a typical procedure.



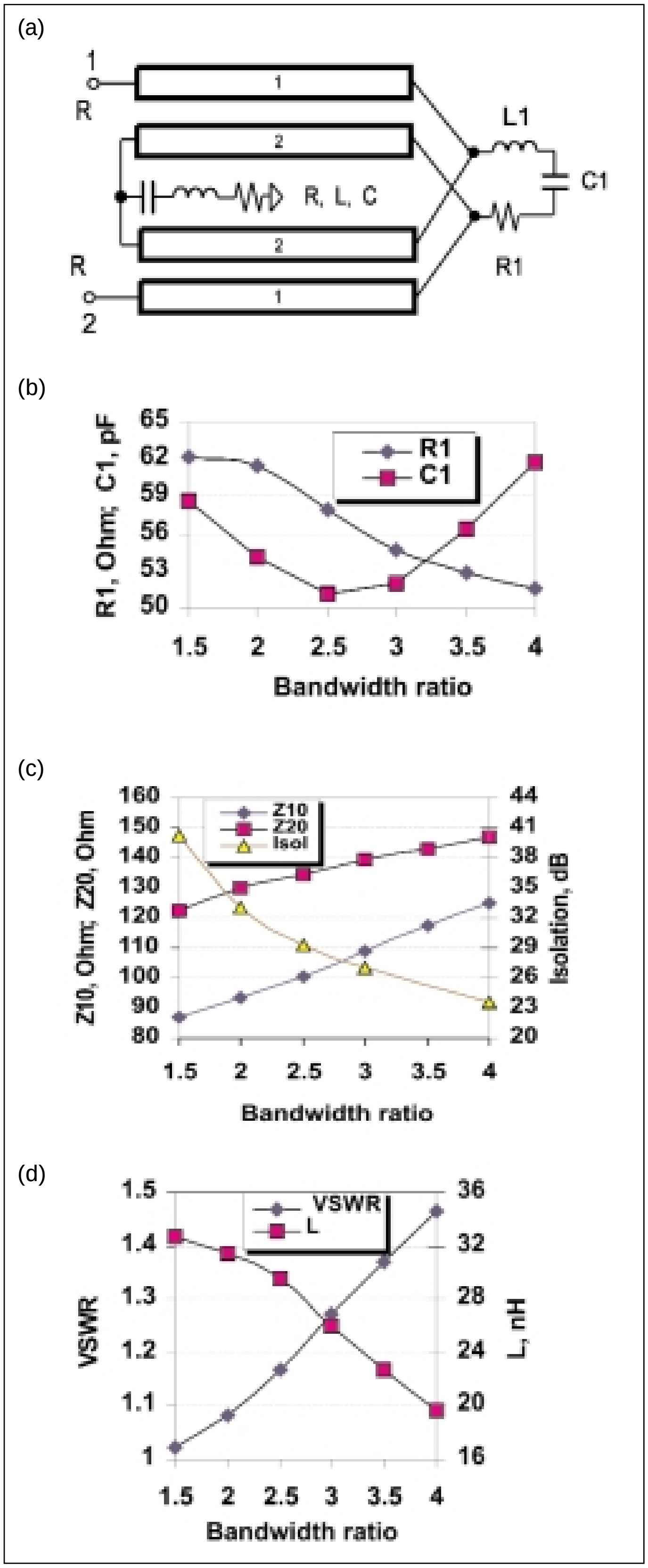
▲ **Figure 8. Two-way combiner with second order band-pass LC-correction.**

For optimum performance, the operating frequency bands with lumped correcting elements are slightly offset to lower frequencies relative to frequency bands without correction (arithmetical symmetry with respect to the quarter-wavelength frequency of the conductors of the coupled line). Instead of LC-elements, open-circuited at the far end, a low-impedance transmission line could be used. In this case, the isolation is superior and a frequency offset is not necessary. A more complicated isolating circuit also provides a further increase of operating bandwidth. For example, the circuit shown in Figure 8 has bandwidth close to 1:20, assuming R_L = R/2. This type of correction can also be used for N-way combiners. For simplicity, the common ground plate is not discussed in this article.

The additional beneficial effect of these isolation-correcting circuits is that they decrease the coupling coefficient between line conductors, and this simplifies practical realizations. Compare, for example, Figure 5(b) and Figure 7(c) for equal bandwidth ratios.

For all considered combiners with symmetrical coupled lines, a well-developed 3-dB coupler's technology can be used. At that time, in the most common practical case, when load impedance and impedances at all inputs are equal, considered combiners should have internal impedance transformation that results in significantly narrowed operating bandwidth. The performances can be improved if additional series LC-circuit are connected to the load, as shown in Figure 9(a).

In the case of internal impedance transformation, each two-conductor line is non-symmetrical, and we numerate conductors defining corresponding independent characteristic impedances: $Z_{10} = 1/Y_{10}$, $Z_{12} = 1/Y_{12}$, $Z_{21} = 1/Y_{21}$ ($Z_{12} = Z_{21}$), and $Z_{20} = 1/Y_{20}$. These imped-



▲ **Figure 9. (a) Two-way combiner with equal port impedances and LC correction circuits; (b) values of isolating elements; (c) characteristic impedances and isolation; and (d) in-phase VSWR and load inductance L.**

ances are interconnected in the π-circuit, and in the same manner corresponding transmission lines are interconnected at both ends. It may be any real non-negative values, because it is a property of characteristic admittances Y_{10}, $Y_{12} = Y_{21}$ and Y_{20}.

For symmetrical coupled lines, $Z_{10} = Z_{20} = Z_e$ and

$$Z_{12} = R\sqrt{\frac{1-k^2}{k}}$$

Figure 9(b-d) shows the results of optimization for the case $R = 50$ ohm, when the electrical length of the coupled line equals 90 degrees at the center frequency $f_0 = 100$ MHz, and for arithmetical symmetry of the lower and upper bands frequencies relative to $f_0 = 100$ MHz. Correcting LC-elements (in nH and pF) are related as

$$\mathrm{L1} \times \mathrm{C1} = \mathrm{L} \times \mathrm{C} = 2533 \quad (5)$$

which corresponds to a resonant frequency of $f_0 = 100$ MHz. Some effect can be achieved using offset in frequencies, as was illustrated for the circuit shown in Figure 7(a). Alternative combinations of VSWR and isolation also take place for different characteristic impedances: Z_{10}, Z_{12} and Z_{20}.

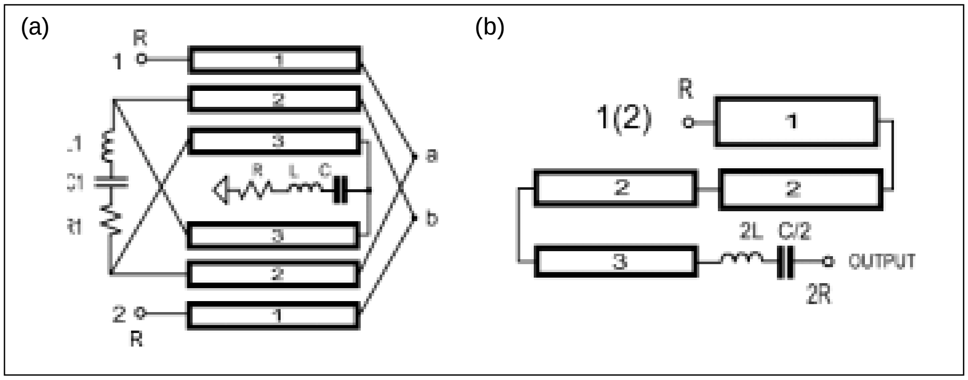
In real designs, there are usually some stray series inductances for connecting to the load and to the isolating resistors. With additional series capacitors, these inductances could play a positive role, if properly adjusted. In any case, there is a significant decrease in bandwidth as a price for an internal impedance transformation.

Besides correction by lumped or distributed elements applied to single section N-way combiners with two-conductor coupled lines, there are other options, such as increasing the number of sections, as is commonly used for Wilkinson combiners or increasing the number of conductors in the coupled lines. In addition, for high bandwidth ratios (as in the case of Figure 8), a broadband transmission-line impedance transformer that is much more compact compared to multiple quarter-wavelength transformer can be used instead of built-in impedance transformation in combiner.

Examples

Compact design can be obtained using three- or multi-conductor coupled transmission lines. Figure 10(a) illustrates a two-way combiner that consists of one quarter-wavelength three-conductor coupled lines with LC-correction and provides equal input and load impedances. An even-mode decomposition circuit is shown in Figure 10(b) for the simplest case in which each three-conductor coupled line has coupling exists only between the adjacent conductors. This circuit defines VSWR at each input (or output VSWR) for in-phase operation. This circuit is a two-step meander-line impedance transformer with additional LC-circuit.

Figure 11(a-c) shows results of optimization for certain values of coupling impedances Z_{12} and Z_{23}, 50-ohm impedances at all ports and central frequency 100 MHz (90 degrees of lines conductors). Inductive elements are defined from (5). Better performance provides additional resistor connected between nodes "a" and "b," as well as offset central frequency, as shown in Figure 7.



▲ **Figure 10. (a) Two-way combiner with 3-conductor coupled lines and (b) its even-mode decomposition circuit.**

Broader bandwidth can be achieved if instead of LC-elements series connected to the load, additional two-way Wilkinson section is used, as shown in Figure 12(a).

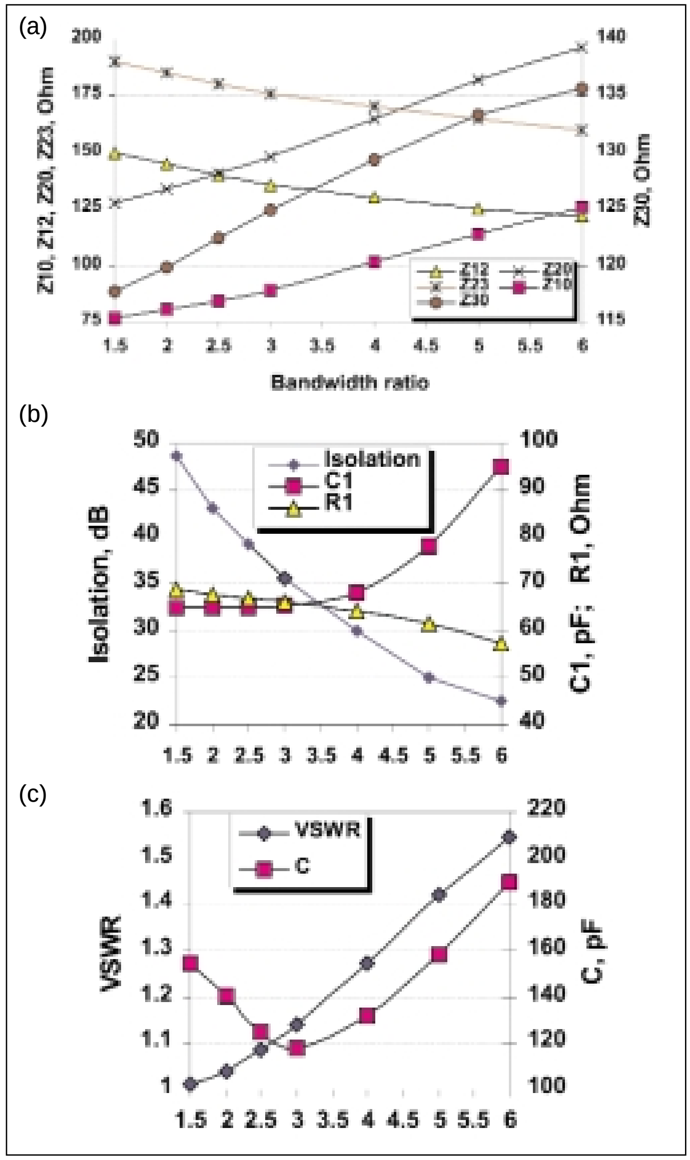
The even-mode decomposition circuit is the same as shown in Figure 10(b), when a single transmission line replaces series LC elements. For a full circuit, as in Figure 12(a), different criteria of optimization could be applied. One result, as a compromise between in-phase VSWR and isolation, is shown in Figure 12(b-d). For this particular case, R = 50 ohms, Z_{30} = 100 ohms, R1 = 150 ohms and center frequency equals 100 MHz. Values of C1 are defined by (5). Other solutions also exist.

Similar results could be achieved in two-section combiner with two-conductor coupled lines in each section. Besides, this type of combiner with symmetrical coupled lines, i.e., without internal impedance transformation (and matched) provides, in particular, 20 dB isolation at bandwidth ratio four octaves, 26 dB at three octaves and 42 dB at two octaves. In addition to Figure 3 and Figures 5 through 8, this demonstrates that without internal impedance transformation, multi-octave bandwidth could be achieved in a simple design.

Conclusion

Novel N-way coupled-line power combiners/splitters are proposed and briefly analyzed. They are based on the use of coupled meander-line impedance transformers (or phase shifters) as in-phase operating (even-mode decomposition) circuits. This approach provides broad bandwidth and relatively small size by using two- and multi-conductor coupled transmission lines.

Simple correction is effectively used for increasing bandwidth and for decreasing coupling coefficients between the line conductors. Grouping of combiner without internal impedance transformation and additional broadband transmission-line transformer is one of the effective ways to achieve multi-octave bandwidth and reasonable size. ■



▲ **Figure 11. Characteristics of a two-way three-conductor line combiner with LC-correction: (a) line impedances; (b) isolation and isolating elements; (c) in-phase VSWR and capacitor values.**

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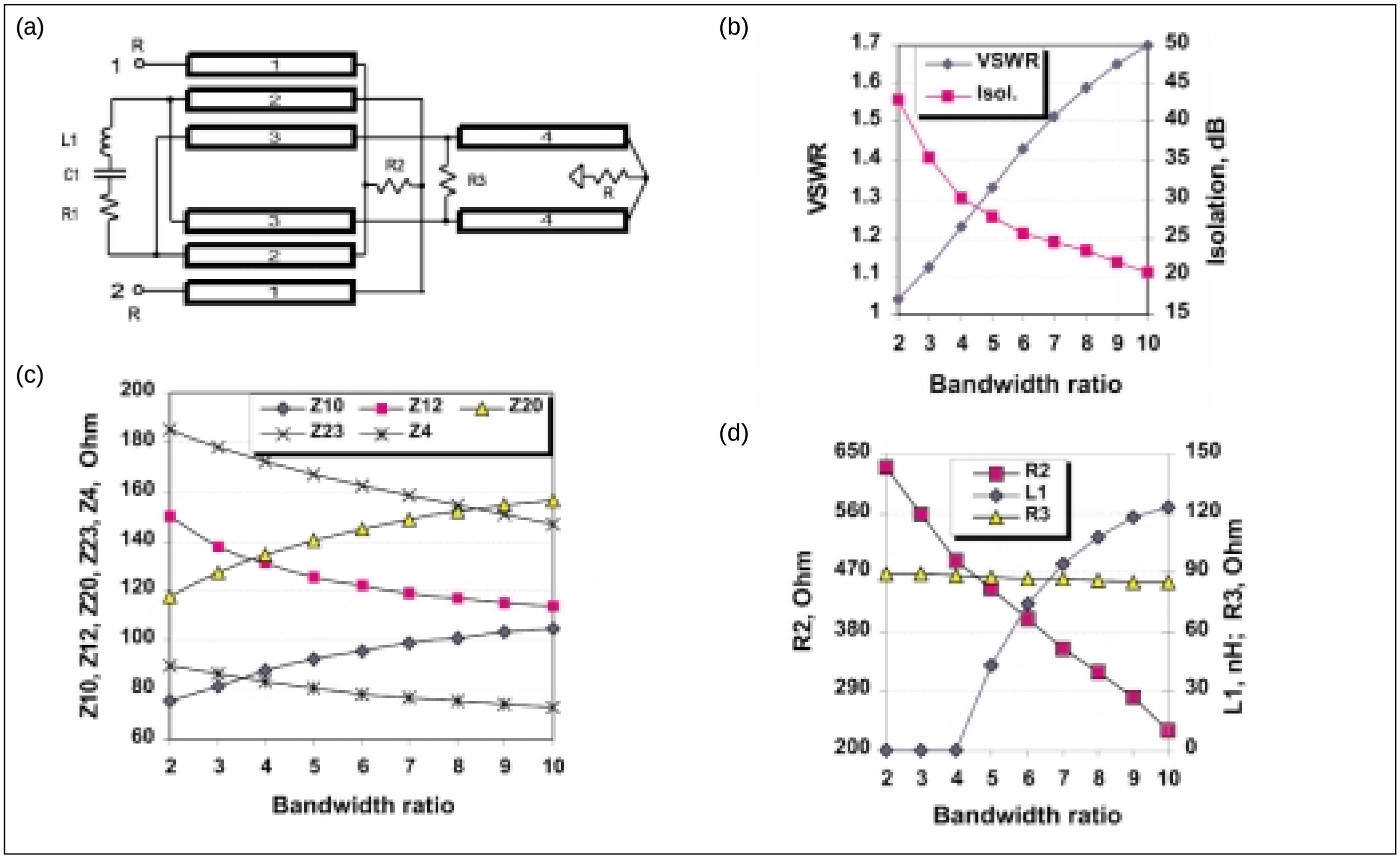

▲ **Figure 12. (a) Two-section coupled-line power combiner and (b-d) its characteristics.**

editorial comments of Dr. Leon Susman and Dave MacEnany, his colleagues at APTI.

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