Power Divider/Combiners: Small Size, Big Specs

A new class of stepped impedance power divider/combiners gives performance comparable to Wilkinson devices at one-third the size. Shorter line length is the secret.

THE Wilkinson family of in-phase, n-way power divider/combiners has been dependable since its introduction in 1960[1]. Now, a new topology has been developed which can match the Wilkinson spec-for-spec, while occupying about one-third the substrate real estate.

Wilkinson devices are strong performers, approaching the ideal in certain respects[2] when realized in microstrip or stripline. If perfect, they would have:

- equal in-phase power division
- one-to-one VSWR at all three ports, and
- infinite isolation between in-phase ports.[3]

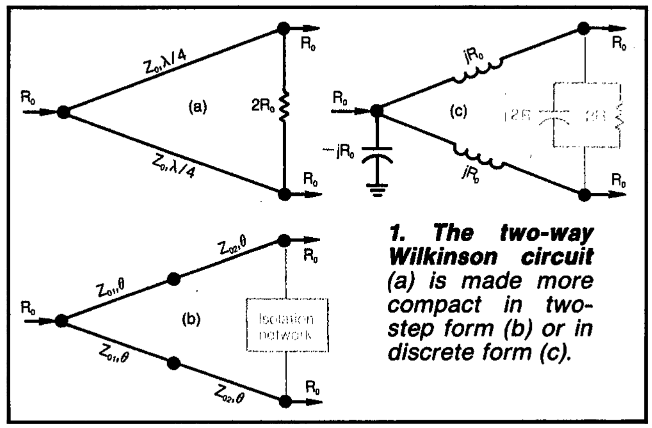
A major disadvantage of the Wilkinson design, however, is the requirement for quarter-wave lines, which are undesirably long below S band. The new alternative to the Wilkinson divider/combiner uses lines of reduced length. The size of the device is drastically reduced, which is especially attractive for L-band operation.

A two-way Wilkinson device is compared with the new configuration in Fig. 1, while the new circuits are shown in parallel and series forms in Fig. 2. The older design uses two parallel impedance transformers, each having a quarter-wavelength transmission line with a characteristic impedance of $\sqrt{2}$ times that of the system's characteristic impedance. When the high-impedance ends are connected in parallel, a power divider/combiner with a system impedance of Z_0 results. The resistance between the two in-phase ports necessary for perfect performance is equal to $2Z_0$.

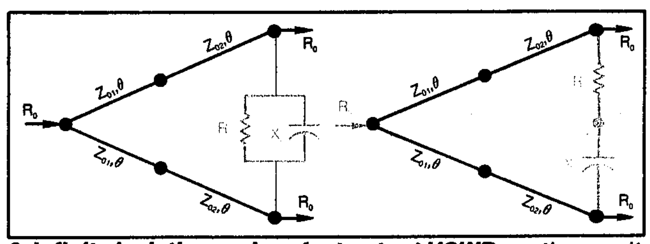
The new device uses stepped impedance transformers with a total line length of less than one-quarter wavelength. As a result, the isolation network requires the addition of a capacitive element (see Fig. 2). The new topology can be fabricated using printed artwork with the addition of only one resistive element per stage. This use of stepped-impedance transmission lines is not new;[4] an even number of alternating high- and low-impedance lines, when cascaded, may be used to transform any real impedance to any other value (see Fig. 1(b)).

The first step in using a two-step transformer as part of a two-way power divider is to make sure that the characteristic impedance R_0 is transformed to $2R_0$. For a given line length θ, impedances Z_{01} and Z_{02} are given by:

$$Z_{01} = \frac{R_0}{\tan\theta}\left[(1 + 8\tan^4\theta)^{\frac{1}{2}} - 1\right]^{\frac{1}{2}} \qquad (1)$$



***1. The two-way Wilkinson circuit** (a) is made more compact in two-step form (b) or in discrete form (c).*



***2. Infinite isolation and perfect output VSWR** are the result when the isolation network in Fig. 1(b) is realized in parallel (a). The series form (b) is also shown.*

$$Z_{02} = \frac{2R_0^2}{Z_{01}} \qquad (2)$$

Equations 1 and 2 generate exact values for Z_{01} and Z_{02} at the design frequency. Over any given bandwidth, a very small band-edge VSWR improvement will result (at the expense of band-center performance) from perturbing Z_{01} and Z_{02} slightly. The enhancement is negligible for bandwidths of less than an octave; still, corrected values are shown in Ref. 4. For practical applications, the use of Fig. 3 with Eqs. 1 and 2 is recommended.

The quantity θ may range anywhere from 0 to 45 degrees for the two-step device; when θ is 45 degrees, the Wilkinson device is created. When $\theta = 0$ degrees, a degenerate solution such as the one shown in Fig. 1(c) is the result.

As the line lengths are reduced below 45 degrees, the following characteristics and limitations apply:

- As θ decreases, Z_{01} decreases and Z_{02} increases. For practical 50-ohm systems using standard substrate materials, line lengths shorter than 15 degrees are generally impractical.

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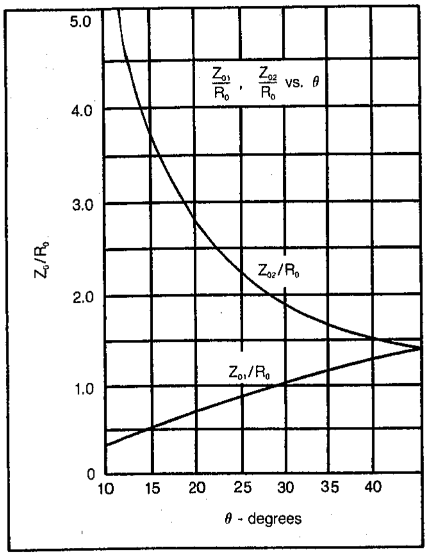
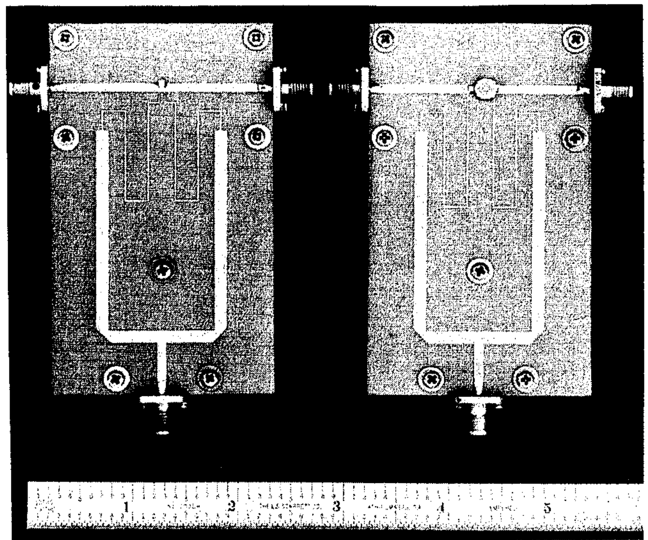


3. Transformation of the characteristic impedance *R_0 follows these curves, in conjunction with Eqs. 1 and 2.*



4. These prototype parallel (left) and series divider/combiner units *operate at 200 MHz.*

Table 1: Allocation of storage registers

Register	Allocation	Register	Allocation
R01	w_0	R08	Z_{02}
R02	R_0	R09	$(Z_{01} + Z_{02})$
R03	θ	R10	$(1+Z_{02}/Z_{01})$
R04	$\sin\theta$	R11	Z_{op}
R05	$\cos\theta$	R12	θ_p
R06	$\tan\theta$	R13	X_s
R07	Z_{01}		

Table 2: Program inputs and printouts

Input	Key	Display	Input	Key	Display
f_0	A	w_0		E	R_s
R_0	B	R_0		R/S	X_s
0	C	Z_{01}		R/S	C_s
	R/S	Z_{02}	Z_{op}	D	Z_{op}
	D	R_p	θ_p	E	R_s
	R/S	X_p		R/S	X_s
	R/S	C_p		R/S	C_s

- For θ between 20 and 25 degrees, Z_{02} reaches an impedance level satisfactory for extensive meandering on most substrates, while there is only moderate reduction in the impedance of Z_{01}.
- The input VSWR is slightly higher than the Wilkinson over bandwidths of 50 percent or less.

The all-important isolation networks

An acceptable, if not perfect, in-phase power divider/combiner must display high isolation between in-phase, low-VSWR ports. In the Wilkinson device, high-isolation, low-VSWR characteristics are achieved via the $2R_0$-ohm resistor. In general, a dissipative element is necessary for proper isolation as well as output matching. Since the electrical length of each 1:2 impedance transformer is less than 90 degrees in the two-step configuration, a capacitive isolation network is needed. The realization of this network is shown in parallel and series forms in Fig. 4.

In the parallel RC network, the solutions for R_p and X_p are given by:

$$R_p = 2R_0 \tag{3}$$

and $X_p = (Z_{01} + Z_{02})^2 \sin\theta \cos\theta$

$$\times \left[Z_{02}\left(1 + \frac{Z_{02}}{Z_{01}}\right)\sin^2\theta - (Z_{01} + Z_{02})\cos^2\theta\right]^{-1} \tag{4}$$

It's interesting to note that R_p does not change in this configuration compared to the Wilkinson device. The solutions for R_s and X_s in the series circuit are given by:

$$R_s = \frac{(Z_{01} + Z_{02})^2}{R_0}\sin^2\theta\cos^2\theta \tag{5}$$

and

$$X_s - 2\left[Z_{02}\left(1 + \frac{Z_{02}}{Z_{01}}\right)\sin^3\theta\cos\theta - (Z_{01} + Z_{02})\sin\theta\cos^3\theta\right] \tag{6}$$

The series arrangement can be altered to include a pad to link the two elements. Modeling the pad as a section of transmission line with a characteristic impedance Z_{op} and electrical length θ_p, the values of R_s and X_s become:

$$R_s = (Z_{01} + Z_{02})^2 \sin^2\theta\cos^2\theta \times \left[R_o\left(\cos\theta_p + \frac{X_s\sin\theta_p}{Z_{op}}\right)\right]^{-1} \tag{7}$$

$$X_s = Z_{op}\sin\theta_p + 2\,Z_{02}\left(1+\frac{Z_{02}}{Z_{01}}\right) - \sin^3\theta\cos\theta - 2\,(Z_{01} + Z_{02})\sin\theta\cos^3\theta\,(\cos\theta_p)^{-1} \tag{8}$$

For these two equations, X_s must be calculated before R_s.

Interesting isolation characteristics

The performance levels of the two-step devices are, on the whole, very similar to those of the Wilkinson devices.

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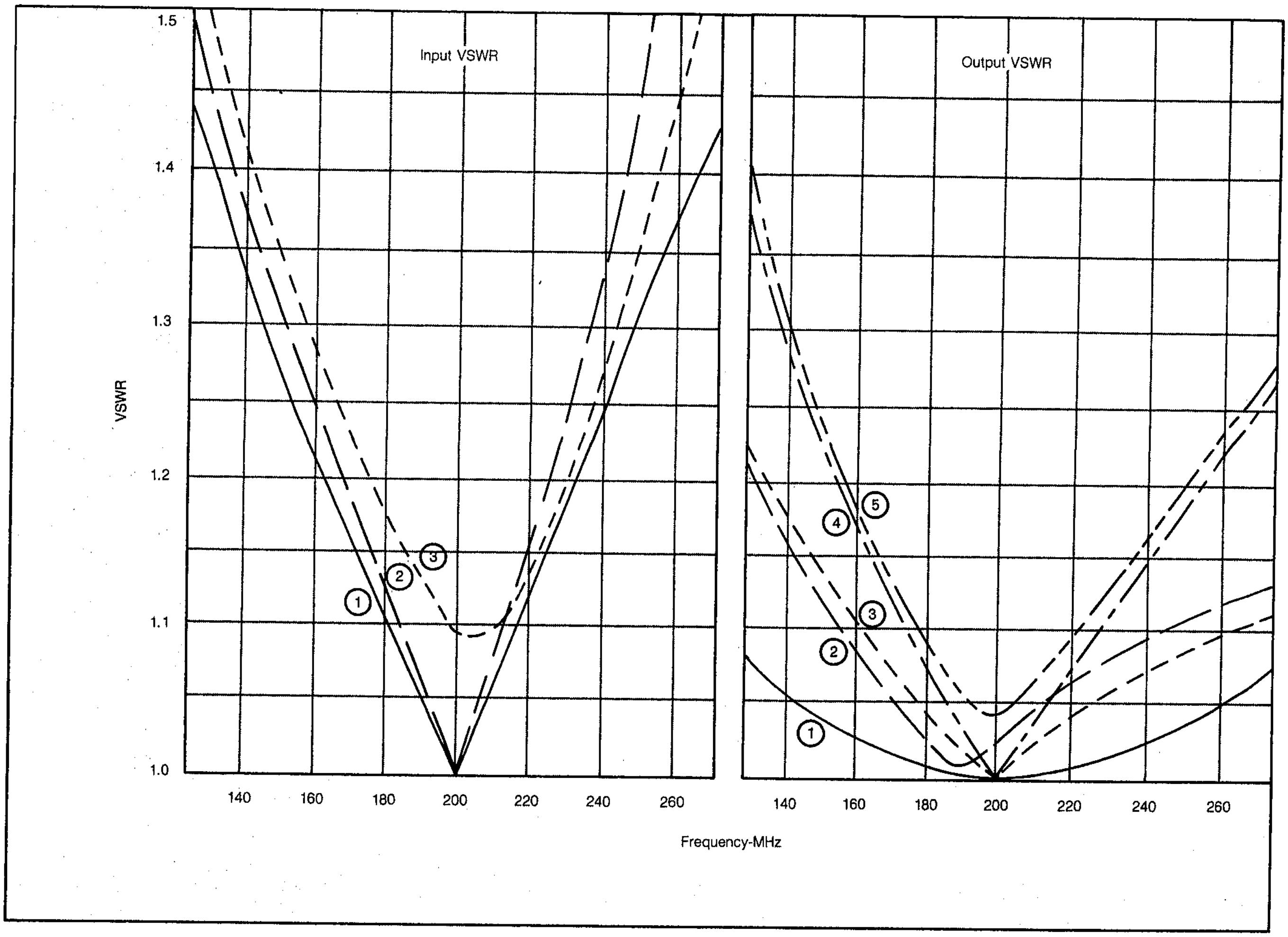
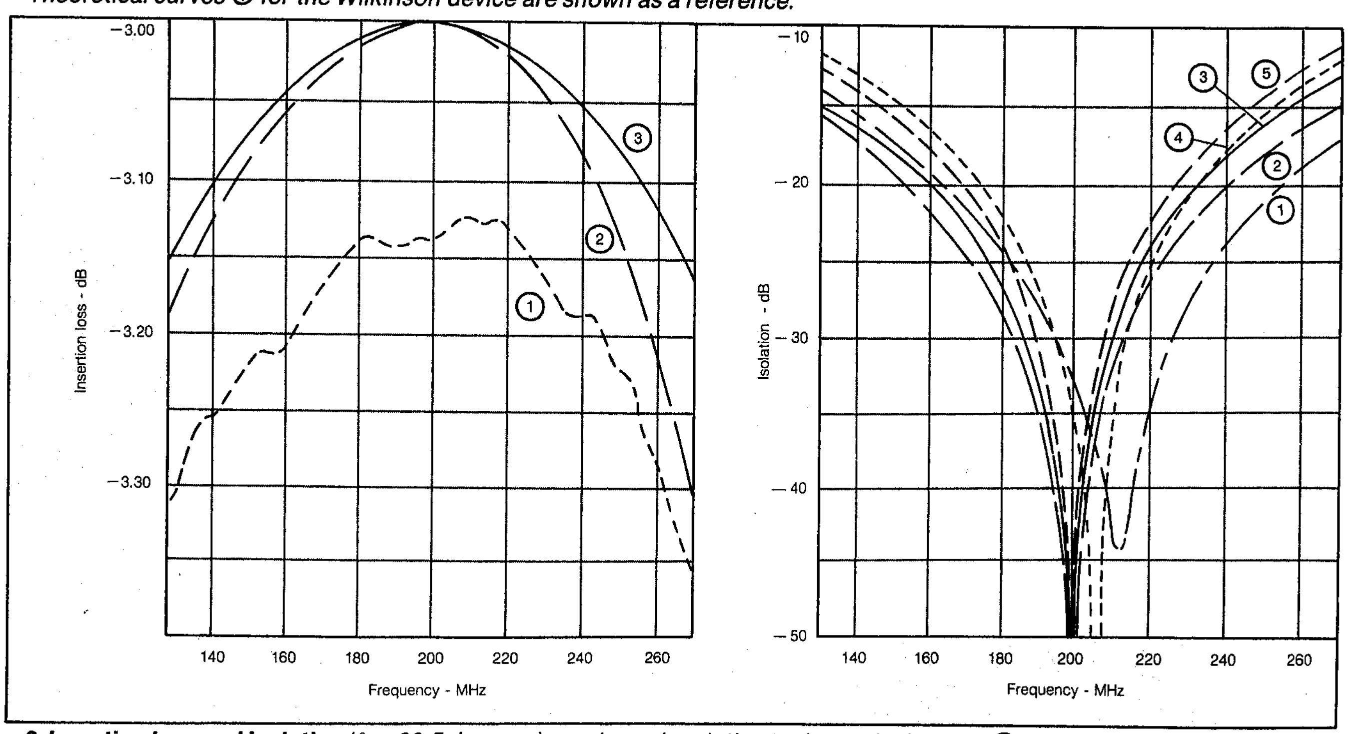
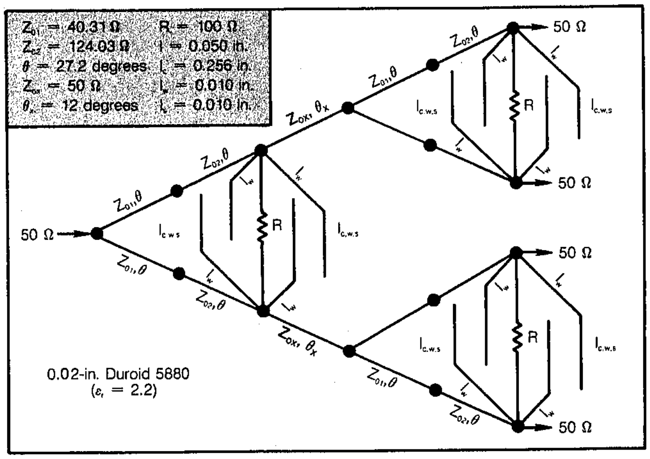


***5. Input and output VSWR are compared** for the two 200-MHz units. The input VSWR curves (left) represent 2 theoretical and 3 measured data for both two-way devices. The output curves show 2 measured and 3 theoretical data for the parallel network, and 4 theoretical and 5 measured data for the series configuration. For all of these curves, $\theta = 22.5$ degrees. Theoretical curves 1 for the Wilkinson device are shown as a reference.*

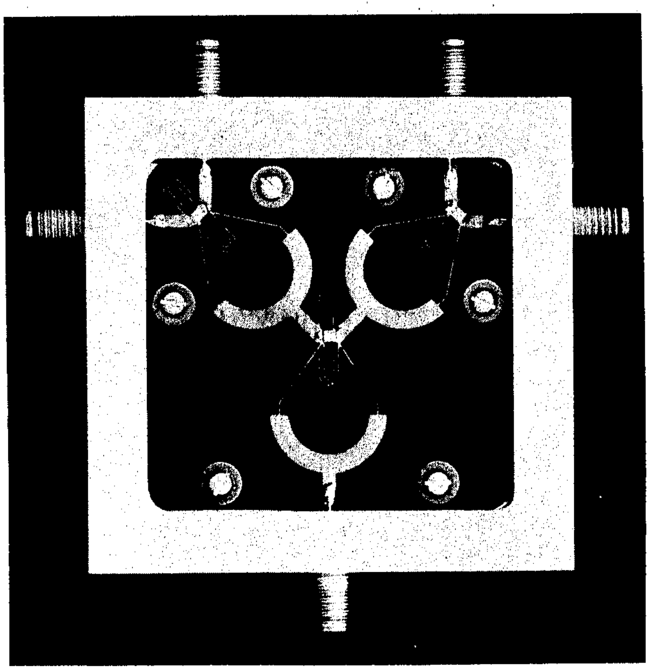


***6. Insertion loss and isolation** ($\theta = 22.5$ degrees) are shown in relation to theoretical curves 3 for the Wilkinson device. The curves at left represent 1 measured and 2 theoretical insertion loss data; the curves at right are 1 measured and 2 theoretical isolation data for the series network compared with the 4 measured and 5 theoretical data for the parallel circuit.*

POWER DIVIDER/COMBINER *(continued from p. 69)*



***7. A four-way divider centered at 2.0 GHz** was built in the parallel RC configuration.*



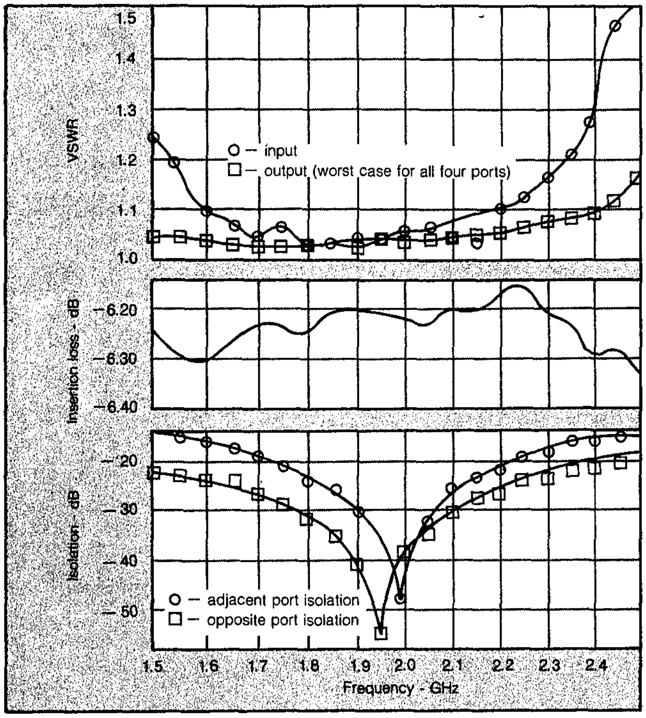
***8. The four-way divider of Fig. 7** was fabricated on 0.002-in. Duroid 5880.*

Since the input VSWR is slightly higher than that of the Wilkinson, the reflective insertion loss will be slightly higher. The dissipative insertion loss will be about the same since the loss reduction due to the shorter lengths of line is virtually canceled out by the increase in dissipation due to the high-impedance line sections.

It should be mentioned that, in the series RC isolation network using an interconnecting line, a very slight degradation in forward response will result due to the effective shunt-pad reactance. The effect is negligible for pads of less than a few degrees in length.

The isolation characteristics of the two-step devices are comparable to the Wilkinson devices. The in-phase port VSWR of the new configuration is higher than that of the Wilkinson, but still acceptable over bandwidths of 50 percent or less. Isolation of the series RC configuration is better than that of the Wilkinson circuit, even when an interconnecting line several degrees in length is used.

Based on the design equations, two prototype units were designed on 0.031-in. woven Teflon fiberglass material with



***9. Performance curves** for the four-way divider show input and output VSWR (top), insertion loss (middle), and isolation (bottom).*

a dielectric constant of 2.55 (Fig. 4). The line lengths were one-sixteenth-wavelength long, and the devices operated at a 200-MHz center frequency. Calculated parameters for the parallel RC network were: R_p = 100 ohms; X_p = −144.19 ohms; C_p = 5.52 pF. For the series network, the values were: R_s = 67.88 ohms; X_s = −46.31 ohms, C_s = 17.18 pF. For both networks, Z_{01} = 40.31 ohms and Z_{02} = 124.03 ohms.

The parallel device was fabricated using a 100-ohm, 50-mil-square chip resistor along with a 5.6-pF, 55-mil-square chip capacitor. The series device uses a 68-ohm chip resistor with a 4- to-18-pF trimmer capacitor set for maximum isolation at 200 MHz. Figures 5 and 6 demonstrate just how well the devices operate, by comparing theoretical performance and measured data with the theoretical performance of a Wilkinson device.

A four-way divider/combiner was fabricated using one two-way circuit to drive two additional two-way circuits. The device, shown in Figs. 7 and 8 in schematic and real-life forms, operates at 2 GHz using the parallel RC topology. Instead of improving isolation by using lumped capacitance, the circuit employs coupled lines.

Gaps and line widths were limited to 10 mils so that standard printed-circuit techniques could be used to fabricate the network. As a result, to achieve the needed interline capacitance, the coupled lines were made long enough to create significant shunt capacitance. Figure 9 shows the performance curves of the component for input and output VSWR, insertion loss, and isolation.

The final geometry of this four-way circuit results from using Tables 1 and 2, in conjunction with the program listing (see "Program listing: Two-step divider/combiner design," p. 74). By allowing the COMPACT program* to

*The program will calculate the parallel RC solution (D, R/S, R/S), the series solution (E, R/S, R/S), or the series R-pad-C solution independently, in any order. For the R-pad-C case, Z_{op} and θ_p must be entered into D', respectively.

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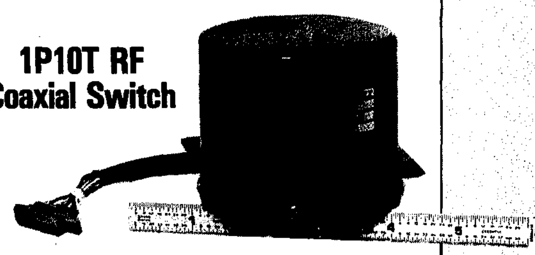

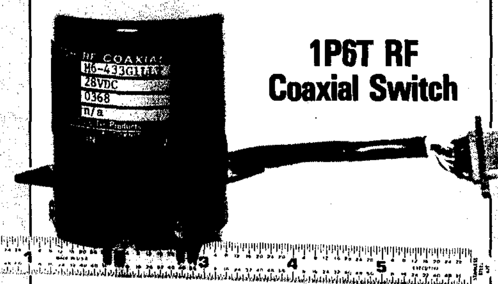

POWER DIVIDER/COMBINERS (continued from p. 73)

Program Listing: Two-step divider/combiner design

STEP	KEY	CODE	STEP	KEY	CODE	STEP	KEY	CODE	STEP	KEY	CODE	STEP	KEY	CODE	STEP	KEY	CODE	STEP	KEY	CODE
000	76	LBL	033	06	06	066	85	+	099	04	04	132	42	STO	165	65	×	198	12	12
001	11	A	034	45	Y^X	067	43	RCL	100	33	X²	133	11	11	166	43	RCL	199	39	COS
002	65	×	035	04	4	068	07	07	101	75	-	134	00	0	167	05	05	200	54	)
003	02	2	036	65	×	069	54	)	102	43	RCL	135	42	STO	168	75	-	201	35	1/X
004	65	×	037	08	8	070	42	STO	103	09	09	136	12	12	169	02	2	202	55	÷
005	89	π	038	85	+	071	09	09	104	65	×	137	61	GTO	170	65	×	203	43	RCL
006	54	)	039	01	1	072	55	÷	105	43	RCL	138	10	E'	171	43	RCL	204	02	02
007	42	STO	040	54	)	073	43	RCL	106	05	05	139	76	LBL	172	09	09	205	65	×
008	01	01	041	34	√X	074	07	07	107	33	X²	140	19	D'	173	65	×	206	43	RCL
009	91	R/S	042	75	-	075	54	)	108	54	)	141	42	STO	174	43	RCL	207	09	09
010	76	LBL	043	01	1	076	42	STO	109	35	1/X	142	11	11	175	04	04	208	33	X²
011	12	B	044	54	)	077	10	10	110	65	×	143	91	R/S	176	65	×	209	65	×
012	42	STO	045	34	√X	078	43	RCL	111	43	RCL	144	76	LBL	177	43	RCL	210	43	RCL
013	02	02	046	65	×	079	08	08	112	09	09	145	10	E'	178	05	05	211	04	04
014	22	INV	047	43	RCL	080	91	R/S	113	33	X²	146	42	STO	179	45	Y^X	212	33	X²
015	52	EE	048	02	02	081	43	RCL	114	65	×	147	12	12	180	03	3	213	65	×
016	91	R/S	049	55	÷	082	08	08	115	43	RCL	148	38	SIN	181	54	)	214	43	RCL
017	76	LBL	050	43	RCL	083	91	R/S	116	04	04	149	65	×	182	55	÷	215	05	05
018	13	C	051	06	06	084	76	LBL	117	65	×	150	43	RCL	183	43	RCL	216	33	X²
019	42	STO	052	54	)	085	14	D	118	43	RCL	151	11	11	184	12	12	217	54	)
020	03	03	053	42	STO	086	02	2	119	05	05	152	85	+	185	39	COS	218	91	R/S
021	38	SIN	054	07	07	087	65	×	120	54	)	153	02	2	186	54	)	219	43	RCL
022	42	STO	055	91	R/S	088	43	RCL	121	91	R/S	154	65	×	187	42	STO	220	13	13
023	04	04	056	35	1/X	089	02	02	122	94	+/-	155	43	RCL	188	13	13	221	91	R/S
024	43	RCL	057	65	×	090	54	)	123	35	1/X	156	08	08	189	65	×	222	94	+/-
025	03	03	058	02	2	091	91	R/S	124	55	÷	157	65	×	190	43	RCL	223	35	1/X
026	39	COS	059	65	×	092	43	RCL	125	43	RCL	158	43	RCL	191	12	12	224	55	÷
027	42	STO	060	43	RCL	093	08	08	126	01	01	159	10	10	192	38	SIN	225	43	RCL
028	05	05	061	02	02	094	65	×	127	54	)	160	65	×	193	55	÷	226	01	01
029	43	RCL	062	33	X²	095	43	RCL	128	91	R/S	161	43	RCL	194	43	RCL	227	54	)
030	03	03	063	54	)	096	10	10	129	76	LBL	162	04	04	195	11	11	228	91	R/S
031	30	TAN	064	42	STO	097	65	×	130	15	E	163	45	Y^X	196	85	+			
032	42	STO	065	08	08	098	43	RCL	131	01	1	164	03	3	197	43	RCL			

first optimize the coupled lines for isolation and output match, and then re-optimizing the lengths of the transformer sections for optimum input characteristics, a successful design was developed.

The new two-way, in-phase circuit may not be perfect, but it is close enough in performance to the Wilkinson device to stand as a pleasant alternative. The fact that it can be made at about one-third the size, makes it an alternative worth considering. ●●

References

1. E.J. Wilkinson, "An N-Way Hybrid Power Divider," *IRE Transactions on Microwave Theory and Techniques,* Vol. MTT-8, No. 1, pp. 116-118 (January 1960).
2. S. Cohn, "A Class of Broadband, Three-Port to TEM Mode Hybrids," *IEEE Transactions on Microwave Theory and Techniques,* Vol. MTT-16, No. 2, pp. 110-118 (February 1968).
3. U.H. Gysel, "A New N-Way Power Divider/Combiner Suitable for High-Power Applications, *1975 MTT Symposium Digest,* pp. 116-118 (1975).
4. G.L. Matthaei, "Short-Step Chebychev Impedance Transformers," *IEEE Transactions on Microwave Theory and Techniques,* Vol. MTT-15, No. 8, pp. 372-383 (August 1966).