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A Compact N-Way Wilkinson Power Divider Using a Novel Coaxial Cable Implementation for VHF Band

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Abstract—A novel implementation of N-way Wilkinson power divider using series and parallel combination of coaxial cables has been proposed in this paper. This arrangement results in a very compact power divider at VHF and lower frequencies, has good isolation between all the ports and is capable of handling high power with a low insertion loss. Frequency tuning and phase equalisation are easily accomplished using this technique. The measured results on fabricated 7-way and 4-way power dividers exhibited good input and output matching as well as amplitude and phase balance with an overall length of less than $\lambda/8$ at 221 MHz, with potential for further reduction in length.

1. INTRODUCTION

An N-way hybrid power divider, with equal division at all the N output ports has been reported by Wilkinson in his classic paper [1]. This power divider gives isolation between output ports and is fairly easy to design as Wilkinson has provided closed form expressions. For N-way power dividers, where N is more than 2, a planar configuration using microstriplines is not possible as all the isolation resistors need to be connected in a single point while at the same time, care needs to be taken to ensure symmetry of the structure and to avoid crossing over of tracks. A 7-way splitter with a star-connection of resistors is shown in Fig. 1.

The transmission lines used in N-way Wilkinson power dividers are $\lambda_g/4$ in length, where λ_g is the guide wavelength at the frequency of operation f, and have a characteristic impedance $Z_t = Z_0\sqrt{N}$, where Z_0 is the input and output characteristic impedance (assumed to be the same here). The characteristic impedance Z_t is easily realisable in printed circuit configuration by appropriately choosing the conductor width, substrate dielectric constant etc.. However, for a single stage power divider with more than two output ports, the planar configuration using printed circuit or integrated circuit processing or lumped elements becomes difficult to realise as discussed earlier. Also, the board size needed becomes quite large at lower frequencies and there is a limitation on power handling apart from increase in losses and/or decrease in isolation or bandwidth [2]. For more than two and particularly for odd number of output ports, a cylindrical configuration as proposed by Wilkinson [1] is often the best choice. For an N-way splitter, Wilkinson has used a circularly symmetric arrangement of transmission lines and the transmission lines have been fashioned by splitting the hollow inner conductor of a coaxial line into N splines of $\lambda_g/4$ length along with a tapered section for matching to input connector dimensions. Naturally, at VHF and lower frequencies, this type of power divider would be unduly long and complex to fabricate.

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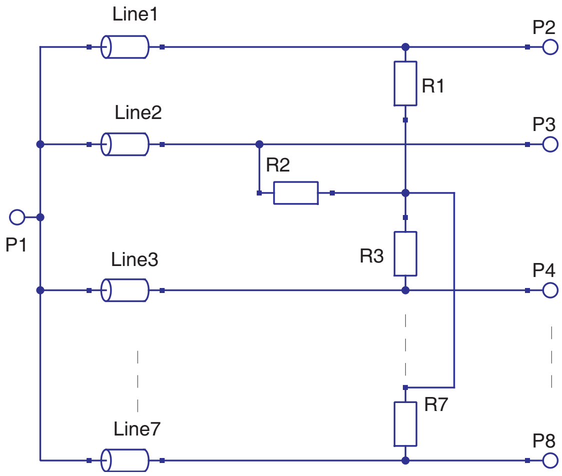


Figure 1. 7-way Wilkinson power divider schematic $Z_t = 132.2\,\Omega$ and length $l = \lambda_g/4$ for all lines $R_1, R_2, \ldots, R_7 = 50\,\Omega$.

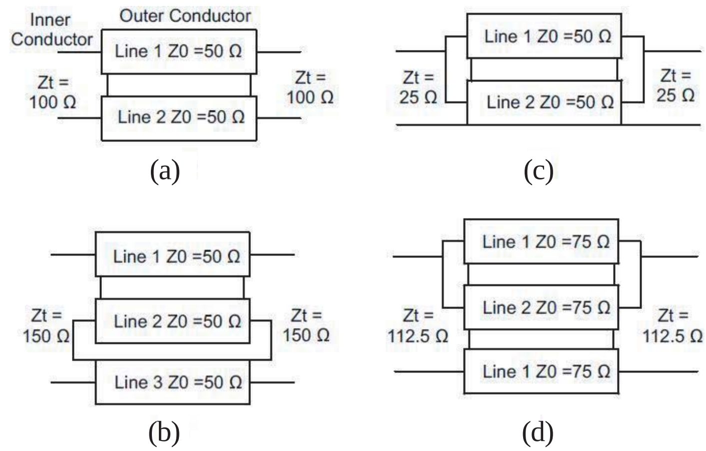


Figure 2. Theoretical Z_t for combinations of (a) coaxial cables and (b) series (c) parallel and (d) series/parallel.

Radial waveguides are often employed for realising N-way power dividers. However, these are without the isolation resistors and thus, give relatively poor isolation between ports [3]. The output ports need to be sufficiently close to facilitate connection of isolation resistors in a star point maintaining sufficiently short and equal path lengths, whereas in radial line power dividers, the ports naturally tend to move away from the common point. A compromise has often been attempted by connecting isolation resistors between adjacent ports rather than in a common point [3]. However, this arrangement is also seen to give poor isolation for opposite ports.

In this paper, a novel arrangement of series and parallel combination of coaxial cables as shown in Fig. 2 has been used as transmission lines with suitable (measured) characteristic impedance of the entire bunch in order to reduce the size of power dividers. Coaxial cables have high power handling capability, are easily available and easy to assemble as compared to the power divider of [1] and are flexible enough to be wound around a core to reduce the overall length. As flexible transmission lines have been used in this design, the output ports may be brought sufficiently close together for the connection of isolation resistors, resulting in excellent isolation characteristics as demonstrated in the next section for a couple of fabricated models. However, for standard coaxial cable implementation, the choice of characteristic impedances available is limited. In the present approach, the required Z_t has been achieved by a series-parallel combination of commonly available coaxial cables as done by George Badger for developing Baluns [4]. Although simple in concept, this technique does not appear to have been exploited so far for the realisation of low loss power dividers with high isolation.

By keeping these coaxial lines beside each other, the bunch becomes flat enough for winding around a core as demonstrated in the fabricated model in the next section. When the bunches of coaxial cables are wrapped in a circularly symmetric fashion around a nonconducting core, it results in a compact power divider with an excellent amplitude and phase balance, low insertion loss and high power handling capability. The amplitude and phase balance depend only upon the symmetry with which the cables are wound and the insertion loss improves since it is a single stage construction employing coaxial cables that are less lossy as compared to, say, microstrip lines. The series and parallel combination of cables employed to realize the desired characteristic impedance increases the power handling capability by approximately the number of cables used. Further, the fine tuning of this type of power divider is easily accomplished by merely trimming the cable length and it does not need elaborate fabrication techniques. Also, using two $50\,\Omega$ cables in series to realise a $100\,\Omega$ transmission line for a 4-way power divider proves to be more robust mechanically, apart from being more cost effective, as compared to, say, a single $93\,\Omega$ cable (closest to $100\,\Omega$) with its more fragile centre conductor.

One 7-way and one 4-way power dividers have been designed, fabricated and measured using this approach, and the results are given in the following sections.

2. DESIGN

For a 7-way Wilkinson power divider as shown in Fig. 1, $N = 7$, and the characteristic impedance needed is $Z_t = Z_0\sqrt{7} = 132.2\,\Omega$. The measured characteristic impedance of two, three, four and five RG 188 ($Z_0 = 50\,\Omega$) and two and three RG 187 ($Z_0 = 75\,\Omega$) cables connected in series similar to that shown in Figs. 2(a) and (b) is given in Table 1. It was experimentally found that due to the coupling between cables, two RG188 coaxial cables in series gave a measured characteristic impedance of $99\,\Omega$, whereas three RG188 coaxial cables in series, as shown in Fig. 2, gave a measured characteristic impedance of $Z_t = 133\,\Omega$ instead of the expected $Z_t = 150\,\Omega$, and for four cables in series, $Z_t = 164\,\Omega$ when actually measured using the technique given in [5]. Similarly, one can use 75 ohm coaxial cables or a combination of 50 and 75 ohm cables in series and parallel as demonstrated in [4] to achieve the required characteristic impedance for a desired N-way power divider, e.g., two $75\,\Omega$ cables in parallel to give $37.5\,\Omega$ and the combination in series with another $75\,\Omega$ cable as shown in Fig. 2(d) to yield an experimentally measured $Z_t = 116\,\Omega$. This characteristic impedance is suitable for a 5 way power divider ($Z_t = 111.8\,\Omega$) with higher power handling capability than individual cables. Thus, from Table 1, two $50\,\Omega$ cables in series have been used for the 4-way power divider. For a 7-way power divider, a transmission line made up of three coaxial cables in series may conveniently be used in Wilkinson configuration with $Z_t = 133\,\Omega$. It may be mentioned here that a 7-way power divider cannot be designed by successively cascading 1 : 2 power dividers and thus, would be difficult to realise in a planar printed circuit microstripline configuration.

Table 1. Measured characteristic impedance of cables in series.

Z_0 (Ω) one cable	Number of cables in series	Measured $Z_t(\Omega)$ cable bunch
50	2	99
	3	133
	4	164
	5	210
75	2	142
	3	186

3. FABRICATION

A 7-way compact power divider has been fabricated using readily available $50\,\Omega$ coaxial cables. Seven transmission lines, each consisting of a bunch of three RG 188 coaxial cables, have been wrapped around a foam core ($\epsilon_r \sim 1$; although a polypropylene core with $\epsilon_r \sim 2.2$ also gave same measured results) in a single turn as shown in Fig. 3(a). The characteristic impedance of the 3 cable bunch and the length required for 90 degree insertion phase were determined experimentally. Each cable bunch is in series with a small section of suspended microstripline at the input side for connection with the input centre conductor. The measured length of this three cable bunch was found to be 23 cm corresponding to $0.245\lambda_g$ at 221 MHz in the coaxial cable with a velocity factor of 0.69 (PTFE dielectric). The wrapping of cables around a core as shown in Fig. 3(a) further reduces the length of the power divider.

The fabricated power divider, open and enclosed, is shown in Fig. 3(a) and Fig. 3(b), respectively. A suspended microstripline of $133\,\Omega$ characteristic impedance has been used for connecting the cable bunches to the input connector. As shown in Fig. 3(a) (left side), the input ends of all the cables have been connected to the suspended microstriplines formed by tracks on a printed circuit board suspended over the common ground plate on the input side. The output side ends of the cable bunch have been brought close together and connected to one end of 1 W carbon composition resistors in the fabricated model [Fig. 3(a) (right side)]. A higher power resistor (with or without heat sink) of suitable power

(a) (b)

Figure 3. Fabricated 7-way power divider — open and enclosed. (a) 7-way power divider assembly (side open). (b) 7-way power divider (enclosed).

handling capability may be used for higher power designs. The other end of all the resistors has been connected in a starpoint similar to that shown in Fig. 1. The cable end connected to resistors has also been connected to 50 Ω microstriplines over a ground plane. The microstriplines have further been connected to output connectors. Finally, the whole assembly has been enclosed within a metal cylinder, effectively shorting the top and bottom plates through the side walls.

The final structure is a closed conducting cylinder of 110 mm length and 160 mm diameter with input (Port1) and output (Port2–Port8) ports as shown in Fig. 3(b). Thus, the length of the power divider has been reduced to $0.117\lambda_g$ (110 mm) at 221 MHz, or less than half of $0.25\lambda_g$ length required in the original Wilkinson configuration and may be reduced further by increasing the number of turns for the cable bunch. Alternatively, a power divider at lower frequencies could also be fabricated with the same overall length, although with more number of turns, thereby making it more compact. It may be noted that fine tuning of the centre frequency or phase equalisation for a particular port is easily accomplished by merely trimming the length of cables as opposed to printed transmission lines or fabrication using splines [1].

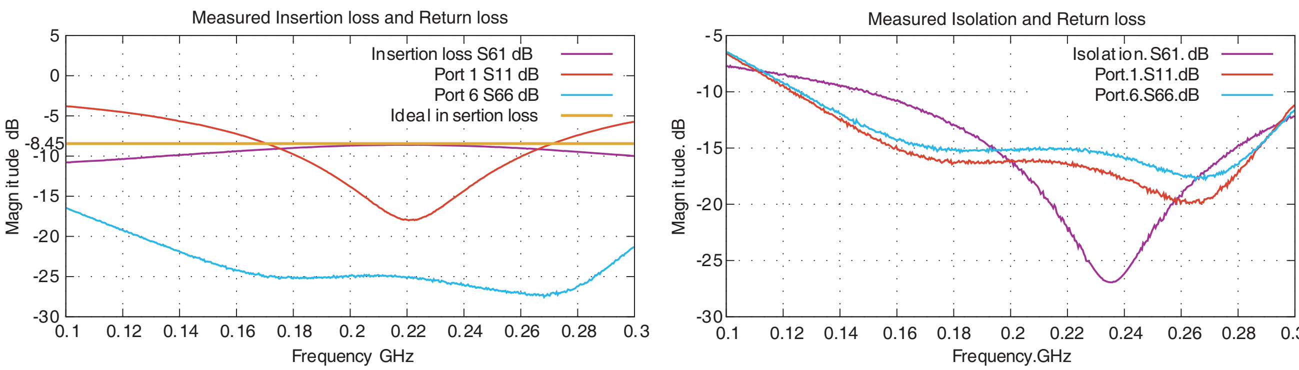
A 1 : 4 power divider has also been fabricated using a similar technique but employing two 50 ohm cables in series to get the required 100 ohm characteristic impedance (or a measured Z_t of 99 ohms). Two power dividers were fabricated as shown in Fig. 4, one straight and other wound on a foam former. The size reduction achieved for 1 : 4 and 1 : 7 power dividers with coiled cables is apparent from Fig. 4. The 4-way power divider has been designed at 200 MHz for which the cables were experimentally found to be 26 cm long for an insertion phase of 90 degrees. After coiling, the size was reduced to 110 mm, or $0.106\lambda_g$ long at 200 MHz.

Figure 4. Fabricated 4-way power dividers — Straight (left) and coiled (centre). Also shown is 7-way enclosed coiled power divider (right) for size comparison.

Thus, it is possible to make an arbitrary N-way compact power divider using a suitable series and parallel combination of 50 ohm or 75 ohm cables.

4. MEASURED RESULTS

Measured results on the fabricated 7-way model are shown in Fig. 5(a) and Fig. 5(b). The three curves in Fig. 5(a) show measured input Port1 return loss, output Port6 return loss and measured insertion loss between Port1 and Port6. It may be seen that the measured centre frequency is 221 MHz and the 2 : 1 VSWR bandwidth is from 182–260 MHz or around 35% and the 15 dB return loss bandwidth is from 204–237 MHz or around 15%. The typical measured insertion loss is 8.65 dB against the theoretical value of 8.45 dB whereas the maximum insertion loss was 8.7 dB for one particular ouput port, giving a maximum 0.25 dB loss in the splitter. It should be remembered that this loss is despite the three cable bunch used as transmission line and includes the connector loss and microstrip loss for input/output connections. The maximum imbalance between ports was found to be ±0.05 dB for amplitude and ±0.2° for phase when measured with a Vector Network Analyser.



(a) (b)

Figure 5. Measured insertion loss and isolation — 7-way power divider. (a) Measured input and output return loss and insertion loss. (b) Measured output return loss and isolation.

The measured values for return loss and isolation plotted in Fig. 5(b) show the return loss of output Port2, output Port6 return loss and isolation between output Port2 and Port6. As seen from Fig. 5(b), the power divider provides a high isolation of better than 32.5 dB between port 2 and port 6 at the design frequency of 221 MHz. The isolation remains better than 23 dB over the entire 2 : 1 VSWR bandwidth. The output port return loss as seen from Fig. 5(b) is better than 25 dB. The measured insertion loss, isolation and return loss are similar for other output ports as shown in Table 2. The inequality in isolation and other characteristics are similar to those noted by Wilkinson [1].

Table 2. Measured insertion loss and isolation for various output ports — 7-way power divider.

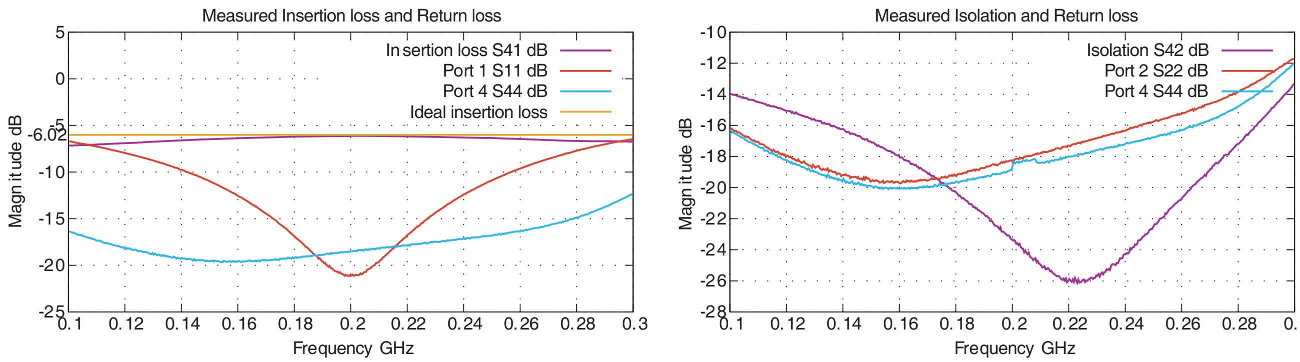
(a) Insertion loss between ports.

between	Return Loss		Insertion loss	
Ports	S_{11}	Output	Mag.	Phase
	dB	dB	dB	deg.
1-2	18.6	26.2	8.63	−110.2
1-3	18.3	26.6	8.63	−110.03
1-4	18.3	25.5	8.63	−110.03
1-5	18.2	28.7	8.7	−110.07
1-6	18.2	25.3	8.62	−110.17
1-7	18.1	29.1	8.69	−110.24
1-8	18.3	26.3	8.6	−110.31

(b) Isolation between ports.

between	Isolation	
Ports	Mag.	Phase
	dB	deg.
2-3	39.6	166
2-4	36	−161
2-5	36	−151
2-6	32.5	−158
2-7	36	−165
2-8	44	160

The measured insertion loss and isolation for a 4-way power divider are shown in Fig. 6. The measured insertion loss and isolation for the coiled 4-way power divider are shown in Table 3. The insertion loss is better than 6.2 dB at the centre frequency of 200 MHz, as against the theoretical value of 6.02 dB and the 2 : 1 VSWR bandwidth is from 143–256 MHz, or 56.5%. The isolation between any two ports is better than 23.3 dB at design frequency.



(a) (b)

Figure 6. Measured insertion loss and isolation — 4-way power divider. (a) Measured input and output return loss and insertion loss. (b) Measured output return loss and isolation.

Table 3. Measured insertion loss and isolation for various output ports — 4-way power divider.

(a) Insertion loss between ports.

between	Return Loss		Insertion loss	
Ports	S_{11}	Output	Mag.	Phase
	dB	dB	dB	deg.
1-2	20.7	18.2	6.17	−101.7
1-3	20.8	23.4	6.15	−103.5
1-4	20.8	18.5	6.14	−102.5
1-5	20.8	18	6.2	−102

(b) Isolation between ports.

between	Isolation	
Ports	Mag.	Phase
	dB	deg.
2-3	26	−140
2-4	23.3	−138
2-5	25.1	−135

5. CONCLUSION

It has been shown that the novel implementation of Wilkinson power dividers using series and parallel combination of coaxial cables enables the design of single stage compact power dividers having good isolation, low insertion loss and capable of handling high power. This technique is simple to realise, affords easy modification of centre frequency, phase equalisation and is useful for designing general N-way power dividers by suitable series/parallel combination of easily and cheaply available cables. Measurements on fabricated 7-way and 4-way power dividers using three and two series connected coaxial cables, respectively, exhibited very good input and output impedance matching, amplitude and phase balance, low insertion loss and good isolation. The size of power dividers was reduced from $\lambda_g/4$ length required in conventional design to less than $\lambda_g/8$, with scope for further reduction. Such compact power dividers are useful as antenna feed networks in a high power phased array of antennas or for power combining from amplifiers, particularly at VHF and lower frequencies where the power divider size may tend to become too restrictive. The technique may easily be extended to the design of unequal power dividers or hybrid couplers.

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