BROADBAND COUPLER DESIGN TABLE

Introduction

This paper contains a table in which the circuit parameters for several types of broadband couplers are tabulated. Handbook methods of designing couplers are described. Couplers having equal or unequal terminating resistances are treated. Equivalent circuits for symmetrical and unsymmetrical circuit configurations using mutual inductance, inductive $-\pi$, inductive - T, and capacitive $-\pi$ coupling are given. Examples illustrating the use of the table and equivalent circuits are included.

Filters designed from the table can be expected to have a passband peak-to-valley ratio of less than 1 db for bandwidths as large as 50% of the midband frequency.

The circuit parameters for the symmetrical coupler configurations are given in a normalized form in which the input and output terminations are each 1 ohm. The midband frequency is 1 cps and bandwidths at the 1 db down points are given in percent of the midband frequency.

References covering broadband coupler-circuits are included. The articles by Dishal,[7] Dougharty,[8] Beam,[9] and Valley and Wallman,[10] are of most direct interest. Dishal presents a number of charts from which it is possible to determine circuit parameters, gain, and bandwidths for various attenuations relative to the peak response for double-tuned couplers having percentage bandwidths on the order of 20% or less. The table contained in this paper eliminates most of the computational work involved in using Dishal's charts and is applicable to couplers having percentage bandwidths as great as 50%. Beam's paper contains the design equations upon which Table I is based. Valley and Wallman present considerable information regarding the construction, measurement and alignment of broadband couplers.

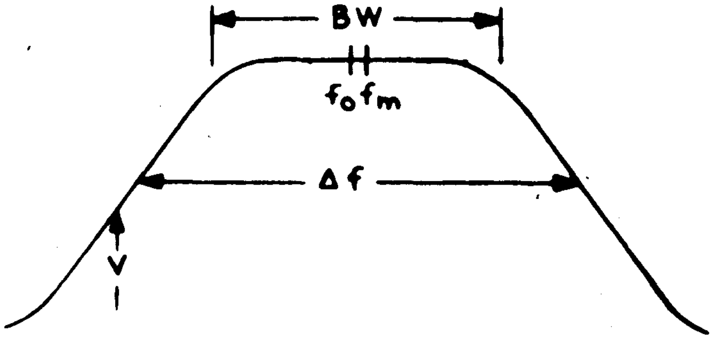
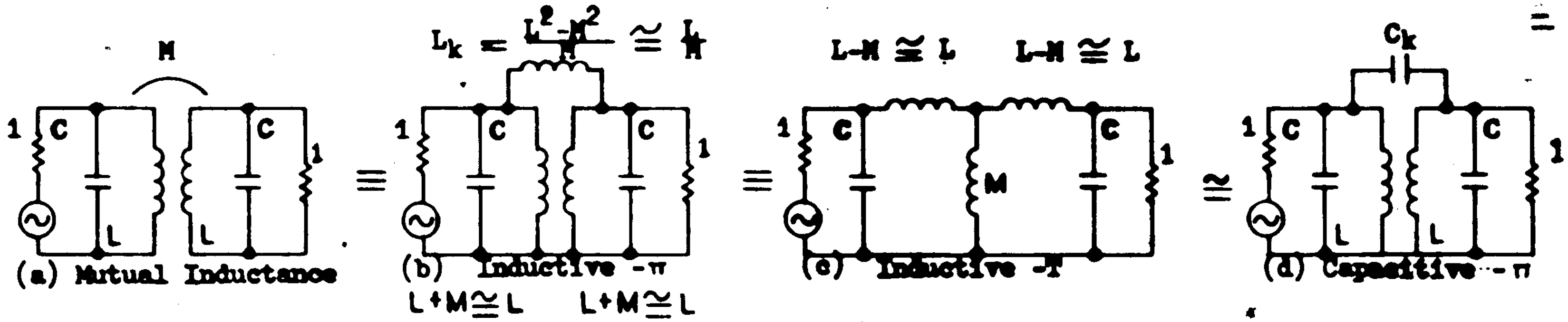


FIGURE 1. BROADBAND COUPLER RESPONSE CURVE

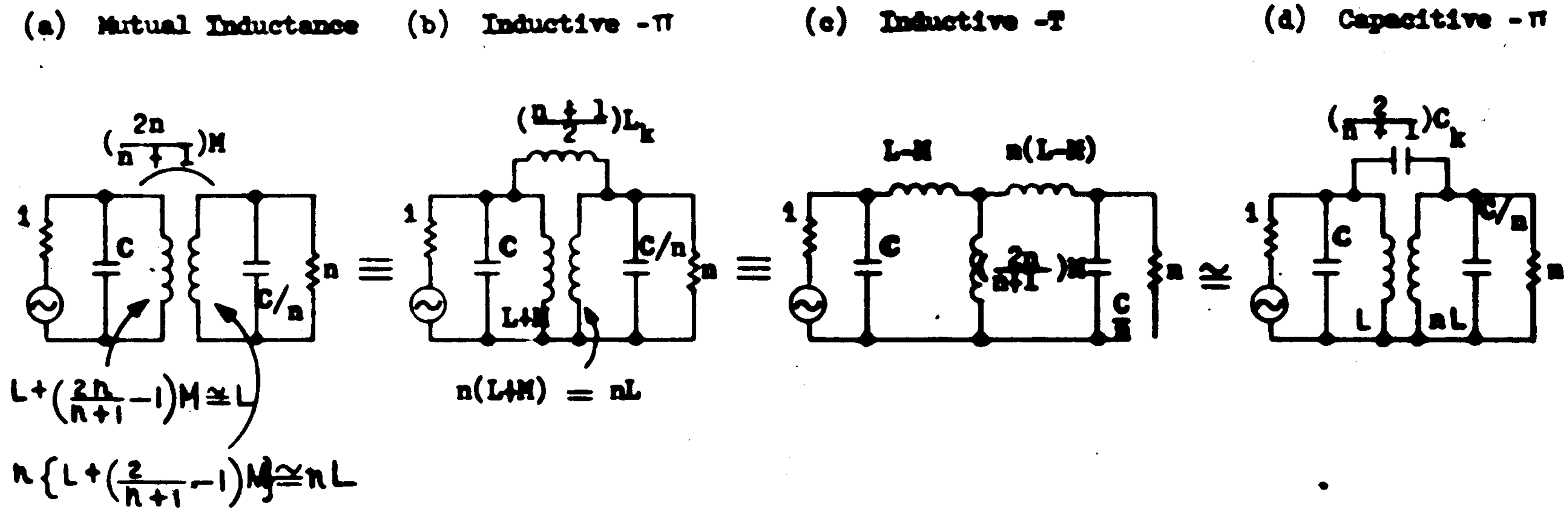
TABLE 1. BROADBAND COUPLER CIRCUIT PARAMETERS

% BANDWIDTH	1%	5%	10%	20%	30%	40%	50%
l	1.58×10^{-3}	7.94×10^{-3}	1.64×10^{-2}	3.21×10^{-2}	4.94×10^{-2}	6.72×10^{-2}	8.69×10^{-2}
c	1.61×10^{1}	3.19	1.55	8.05×10^{-1}	5.36×10^{-1}	4.07×10^{-1}	3.28×10^{-1}
m	1.56×10^{-5}	3.96×10^{-4}	1.69×10^{-3}	6.42×10^{-3}	1.44×10^{-2}	2.53×10^{-2}	3.98×10^{-2}
$l-m$	1.56×10^{-3}	7.90×10^{-3}	1.47×10^{-2}	2.57×10^{-2}	3.50×10^{-2}	4.19×10^{-2}	4.71×10^{-2}
l_k	1.60×10^{-1}	1.59×10^{-1}	1.57×10^{-1}	1.56×10^{-1}	1.55×10^{-1}	1.53×10^{-1}	1.50×10^{-1}
c_k	1.59×10^{-1}	1.68×10^{-1}	1.78×10^{-1}				
k	9.90×10^{-3}	4.99×10^{-2}	1.03×10^{-1}	2.00×10^{-1}	2.91×10^{-1}	3.77×10^{-1}	4.58×10^{-1}
f_o	1.000	1.000	1.000	.990	.978	.962	.943
$l+m$	1.60×10^{-3}	8.34×10^{-3}	1.81×10^{-2}	3.85×10^{-2}	6.38×10^{-2}	9.25×10^{-2}	1.27×10^{-1}



(a) Mutual Inductance (b) Inductive -π (c) Inductive -T (d) Capacitive -π

FIGURE 2. EQUIVALENT CIRCUITS FOR SYMMETRICAL CONFIGURATIONS. THE CIRCUIT PARAMETERS ARE TABULATED IN TABLE 1.



(a) Mutual Inductance (b) Inductive -π (c) Inductive -T (d) Capacitive -π

FIGURE 3. EQUIVALENT CIRCUITS FOR NONSYMMETRICAL CONFIGURATIONS.

The letter n is the ratio of desired output to input resistance. The other symbols refer to the prototype sections in Figure 2.

NOTES REGARDING THE TABLE

1. The parameters tabulated refer to the normalized circuits of Figures 1, (a), (b), (c) and (d) in which the source and load impedances are each 1 ohm, the midband frequency, f_m, is 1 cps and bandwidths are given in percent of the midband frequency.
2. In the text, a capital letter, L, for example, means that the de-normalized parameter is being referred to. Lower case letters refer to the normalized circuit parameters tabulated in Table I.
3. The symmetrical configurations of Figure 2 are used when the source and load impedances are equal. The unsymmetrical configurations of Figure 3 are used when the source and load impedances are unequal.
4. For computing bandwidths at the 10 db, 20 db, and 30 db down points, the following formulae computed from Dishal's charts are useful:[3]

   a) BW(10 db) = 3.3 x BW(1 db)

   b) BW(20 db) = 5.8 x BW(1 db)

   c) BW(30 db) = 10 x BW(1 db)

USE OF THE TABLE

Symmetrical Configurations

To compute the circuit parameters for a coupler similar to one included in Figure 2, the following procedure may be followed:

1) Determine the midband frequency, f_m, from

$$f_m = \sqrt{f_1 f_2}$$

where f_1 and f_2 are the passband limits measured at the 1 db down points.

2) Determine the percentage bandwidth required from

$$\%BW = \frac{f_2 - f_1}{f_m} \times 100$$

Use the next greater tabulated percentage bandwidth.

3) From Table I find the normalised circuit parameters required for the particular circuit configuration selected under the % bandwidth column determined in step (2).

4) Convert the normalized circuit parameters to the required (denormalised) values by multiplying by the proper denormalising factor; $(\frac{R}{f_m})$ for inductances and $(\frac{1}{f_m R})$ for capacitances; i.e.,

$$L = l\left(\frac{R}{f_m}\right) \text{ Henry}$$

$$C = c\left(\frac{1}{f_m R}\right) \text{ Farad}$$

where l and c refer to the tabulated normalised inductance and capacitance, respectively. f_m is the midband frequency in cps computed in step (1), R is the value of the desired source resistance in ohms, and L and C are the denormalised inductance and capacitance in Henrys and Farads, respectively. The denormalisation procedure is illustrated in Examples 1 and 2.

Nonsymmetrical Configurations

In the event that it is desired to change the ratio of load-to-source impedance by a factor n, the equivalent circuits shown in Figure 3 may be used. The procedure to be used is essentially the same as that used for the symmetrical cases and is illustrated in Example 3.

Example 1: Design a bandpass coupler using mutual inductance coupling in the form of a doubly parallel tuned transformer having load and source impedances of 10,000 ohms and a passband extending from 13.650 mcs. to 14.350 mcs at the 1 db points.

$$f_m = \sqrt{1.36 \times 10^6 \times 1.430 \times 10^6} = 1.4 \times 10^7 \text{ cps}$$

$$R = 10^4 \text{ ohms}$$

$$\%BW = \frac{7.00 \times 10^5}{1.40 \times 10^7} \times 10^2 = 5\%, \qquad \frac{R}{f_m} = 7.14 \times 10^{-4} \ \frac{\text{ohms}}{\text{cps}}$$

$$\frac{1}{f_m R} = 7.14 \times 10^{-12} \ \frac{1}{\text{cps} \times \text{ohms}}$$

Using the equivalent circuit of Figure 2 (a) and substituting in the denormalization formulae given previously, we have:

$$L = l \left(\frac{R}{f_m}\right) = 7.94 \times 10^{-3} \times 7.14 \times 10^{-4} = 5.68 \times 10^{-6} \text{ Henry}$$

$$C = c \left(\frac{1}{f_m R}\right) = 3.19 \times 7.14 \times 10^{-12} = 2.28 \times 10^{-11} \text{ Farad}$$

$$M = m \left(\frac{R}{f_m}\right) = 3.96 \times 10^{-4} \times 7.14 \times 10^{-4} = 2.83 \times 10^{-7} \text{ Henry}$$

Example 2: Design a bandpass coupler equivalent to that of Example 1 but using an inductive -π configuration.

Using the equivalent circuit of Figure 2 (b) and the circuit parameters computed in Example 1, we have:

$$f_m = 1.4 \times 10^7 \text{ cps}, \qquad R = 10^4 \text{ ohms}, \qquad \%BW = 5\%$$

$$C = 2.28 \times 10^{-11} \text{ Farad}, \qquad \frac{R}{f_m} = 7.14 \times 10^{-4} \ \frac{\text{ohms}}{\text{cps}}$$

From Table I, $(l + m) = 8.34 \times 10^{-3}$ Henry and

$l_k = 1.59 \times 10^{-1}$ Henry

Denormalizing:

$$(L + M) = (l + m)\left(\frac{R}{f_m}\right) = 8.34 \times 10^{-3} \times 7.14 \times 10^{-4} = 5.96 \times 10^{-6} \text{ Henry}$$

$$L_k = l_k \left(\frac{R}{f_m}\right) = 1.59 \times 10^{-1} \times 7.14 \times 10^{-4} = 1.14 \times 10^{-4} \text{ Henry}$$

Example 3: Design a bandpass coupler using the double-tuned transformer configuration of Figure 2 (a) having characteristics identical to those of the coupler of Example 1 except that a 20 K ohm output termination is required. Using the equivalent circuit of Figure 3 (a) for the nonsymmetrical configuration and the circuit parameters computed in Example 1, we have

$$f_m = 1.4 \times 10^{7} \text{ cps}, \quad R = 10^{4} \text{ ohms},$$

$$C = 2.28 \times 10^{-11} \text{ Farad}$$

$$n = 2$$

$$L + \left(\frac{2n}{n+1} - 1\right) M = 5.68 \times 10^{-6} + \left(\frac{4}{3} - 1\right) 2.83 \times 10^{-7}$$

$$= 5.77 \times 10^{-6} \text{ Henry}$$

$$n \left\{ L + \left(\frac{2}{n+1} - 1\right) M \right\} = 11.2 \times 10^{-6} \text{ Henry}$$

$$\frac{C}{n} = 1.14 \times 10^{-11} \text{ Farad}$$

Practical Considerations

The doubly-tuned air core transformer realization of the coupler is usually practical for percentage bandwidths less than 30%. Couplers utilizing carbonyl-iron core transformers are practical for percentage bandwidths of up to about 50%. The larger percentage bandwidths may be achieved with the inductive -π or - T sections.

The π and T sections are usually the easiest to fabricate although they may be somewhat bulkier and more expensive.

The capacitive -π coupler, for which circuit values are tabulated in Table I, is practical for percentage bandwidths of about 10%, however, because of its poor phase response, it is usually not suitable for larger bandwidths.[8]

In the case of the transformer realization of the coupler, the correct spacing of the windings may be determined as follows:

1) Adjust each winding to resonate with the design capacity at f_o with the other winding open circuited.

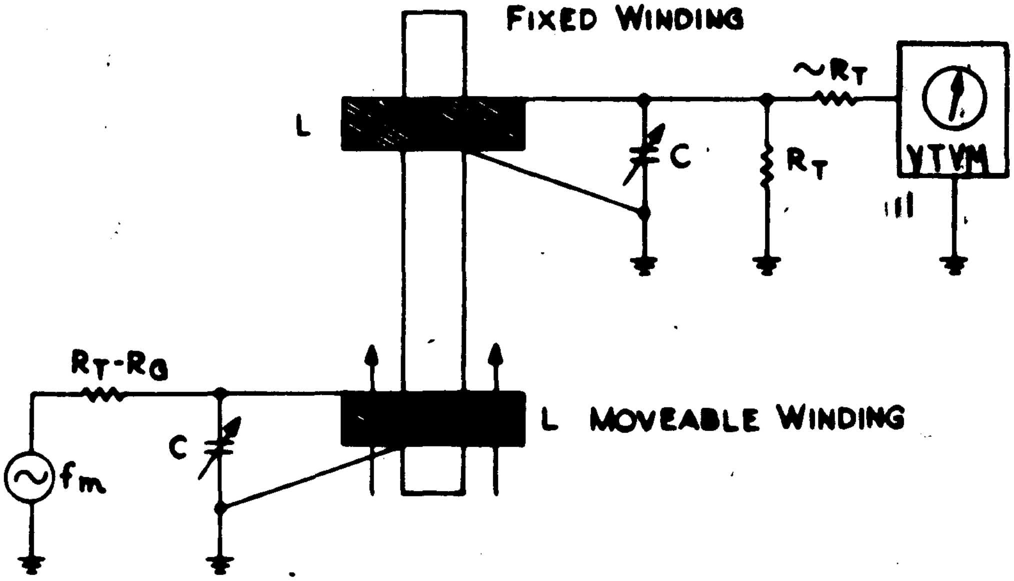
2) Determine the proper terminating resistors by means of an impedance bridge or Q-Meter remembering that the actual value of the terminating resistor may be several times as large as the design value due to the effects of coil loss. The indicated equivalent circuit parallel resistance of each coil with the terminating resistor in parallel when measured at the midband frequency by an impedance bridge should equal the design value.

3) Using the test setup shown in Figure 4, adjust the mutual inductance by pushing the coils together until the meter peaks. Check band limits and passband flatness.

In the cases of other than the transformer realization of the coupler, it is usually sufficient to adjust the various circuit components to the design values on an impedance bridge at the midband frequency.

Further design and construction information is contained in Reference 10.

FIGURE 4. TUNED TRANSFORMER COUPLER ALIGNMENT PROCEDURE



R_G = signal generator output impedance

R_T = coupler terminating resistance as determined by means of an impedance bridge or Q-meter as indicated in the text

Each coil is adjusted to resonate at the tune frequency, f_o, with the other coil open circuited. With both coils independently adjusted to resonance, one coil is pushed toward the other until the VTVM peaks. Bandwidth limits and passband flatness are then checked.

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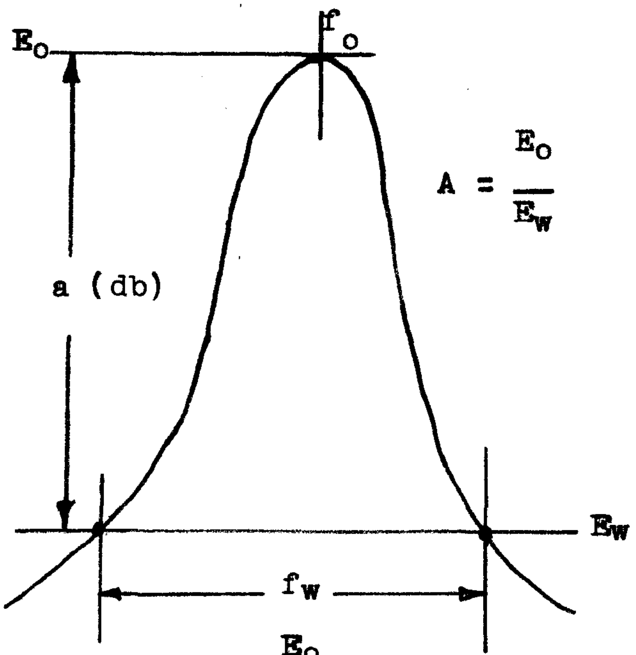
11. E. Gruen, "A Network Theorem," pp. 35-38, *Marconi Review*, No. 125, Vol. XX; 1957.

T. Clemens

BANDWIDTH AND ATTENUATION OF CASCADED TUNED CIRCUITS



$A = \frac{E_o}{E_w}$

$a = 20 \log_{10} \frac{E_o}{E_w}.$

f_o = resonant frequency of all circuits;

a = overall attenuation off resonance; and

f_w = overall bandwidth in same units as f_o.

Value of bandwidth,

$$f_w = Wf_o/Q,$$

where W = bandwidth factor from table; and $Q = L/R$, assumed same for all circuits.

Other expressions of the formula;
$Q = Wf_o/f_w$,
and $W = Qf_w/f_o$.

The formulas which are the basis of the table are:

$$\left.\begin{aligned} W &= (A^{2/n} - 1)^{1/2} \\ A &= (1 + W^2)^{n/2} \end{aligned}\right\} \text{Very Loose Coupling}$$

$$\left.\begin{aligned} W &= \sqrt{2}\,(A^{4/n} - 1)^{1/4} \\ A &= \left(1 + \frac{W4}{4}\right)^{n/4} \end{aligned}\right\} \text{Optimum Coupling}$$

Here n = total number of circuits.

<table>
<tr><th rowspan="2">Total Number of Circuits n</th><th colspan="7">BANDWIDTH FACTOR, W</th></tr>
<tr><th>A=1.12
a=1db</th><th>A=1.26
a=2db</th><th>A=1.41
a=3db</th><th>A=2
a=6db</th><th>A=4
a=12db</th><th>A=7
a=17db</th><th>A=10
a=20db</th></tr>
<tr><td colspan="8">CIRCUITS OF EQUAL INDIVIDUAL SELECTIVITY VERY LOOSELY COUPLED OR CASCADED IN SUCCESIVE STAGES OF AN AMPLIFIER
For A=1.12 thru A=10</td></tr>
<tr><td>1</td><td>0.51</td><td>0.77</td><td>1.00</td><td>1.73</td><td>3.9</td><td>6.9</td><td>10</td></tr>
<tr><td>2</td><td>0.35</td><td>0.51</td><td>0.64</td><td>1.00</td><td>1.7</td><td>2.2</td><td>3</td></tr>
<tr><td>3</td><td>0.28</td><td>0.41</td><td>0.51</td><td>0.77</td><td>1.2</td><td>1.7</td><td>1.9</td></tr>
<tr><td>4</td><td>0.24</td><td>0.35</td><td>0.44</td><td>0.64</td><td>1.0</td><td>1.3</td><td>1.5</td></tr>
<tr><td>5</td><td>0.22</td><td>0.31</td><td>0.39</td><td>0.57</td><td>0.86</td><td>1.1</td><td>1.2</td></tr>
<tr><td>6</td><td>0.20</td><td>0.28</td><td>0.35</td><td>0.51</td><td>0.77</td><td>0.96</td><td>1.1</td></tr>
<tr><td>7</td><td>0.18</td><td>0.26</td><td>0.32</td><td>0.47</td><td>0.70</td><td>0.86</td><td>0.96</td></tr>
<tr><td>8</td><td>0.17</td><td>0.24</td><td>0.30</td><td>0.44</td><td>0.64</td><td>0.79</td><td>0.88</td></tr>
<tr><td colspan="8">CIRCUITS OF EQUAL INDIVIDUAL SELECTIVITY OPTIMUM-COUPLED IN PAIRS
For A=1.12 thru A=10</td></tr>
<tr><td>2(1 pair)</td><td>1.01</td><td>1.24</td><td>1.4</td><td>1.9</td><td>2.8</td><td>3.7</td><td>4.5</td></tr>
<tr><td>4(2 pair)</td><td>0.84</td><td>1.01</td><td>1.1</td><td>1.4</td><td>1.9</td><td>2.2</td><td>2.5</td></tr>
<tr><td>6(3 pair)</td><td>0.75</td><td>0.90</td><td>1.0</td><td>1.2</td><td>1.6</td><td>1.8</td><td>2.0</td></tr>
<tr><td>8(4 pair)</td><td>0.70</td><td>0.84</td><td>0.93</td><td>1.13</td><td>1.4</td><td>1.6</td><td>1.7</td></tr>
<tr><td>10(5 pair)</td><td>0.65</td><td>0.79</td><td>0.88</td><td>1.06</td><td>1.31</td><td>1.47</td><td>1.57</td></tr>
</table>

BANDWIDTH FACTOR, W

CIRCUITS OF EQUAL INDIVIDUAL SELECTIVITY VERY LOOSELY COUPLED OR CASCADED IN SUCESSIVE STAGES OF AN AMPLIFIER

For A= 20 thru A= 10^5

Total Number of Circuits n	A=20 a=26db	A=40 a=32db	A=70 a=37db	A=100 a=40db	A=1000 a=60db	A=10^4 a=80db	A=10^5 a=100db
1	19.9	39.9	70	100	1000	10^4	10^5
2	4.4	6.3	8.3	10	31.6	100	316.3
3	2.5	3.3	4.0	4.5	10	21.5	46.4
4	1.9	2.3	2.7	3.0	5.5	10	17.7
5	1.5	1.8	2.1	2.3	3.9	6.3	10
6	1.3	1.6	1.8	1.9	3.0	4.6	6.8
7	1.16	1.4	1.54	1.65	2.5	3.6	5.1
8	1.06	1.23	1.38	1.47	2.2	3.0	4.0

CIRCUITS OF EQUAL INDIVIDUAL SELECTIVITY OPTIMUM-COUPLED IN PAIRS

For A=20 thru A=10^5

2(1 pair)	6.2	9.0	11.8	14.1	44.7	141.4	447.1
4(2 pair)	3.0	3.5	4.1	4.5	8.0	14.1	25.2
6(3 pair)	2.3	2.6	2.8	3.1	4.5	6.6	9.6
8(4 pair)	1.9	2.2	2.3	2.5	3.5	4.5	6.0
10(5 pair)	1.74	1.92	2.06	2.15	2.78	3.53	4.5

BANDWIDTH FACTOR, W

CIRCUITS OF EQUAL INDIVIDUAL SELECTIVITY VERY LOOSELY COUPLED OR CASCADED IN SUCESSIVE STAGES OF AN AMPLIFIER

For A= 20 thru A= 10^5

Total Number of Circuits n	A=20 a=26db	A=40 a=32db	A=70 a=37db	A=100 a=40db	A=1000 a=60db	A=10^4 a=80db	A=10^5 a=100db
1	19.9	39.9	70	100	1000	10^4	10^5
2	4.4	6.3	8.3	10	31.6	100	316.3
3	2.5	3.3	4.0	4.5	10	21.5	46.4
4	1.9	2.3	2.7	3.0	5.5	10	17.7
5	1.5	1.8	2.1	2.3	3.9	6.3	10
6	1.3	1.6	1.8	1.9	3.0	4.6	6.8
7	1.16	1.4	1.54	1.65	2.5	3.6	5.1
8	1.06	1.23	1.38	1.47	2.2	3.0	4.0

CIRCUITS OF EQUAL INDIVIDUAL SELECTIVITY OPTIMUM-COUPLED IN PAIRS

For A=20 thru A=10^5

Total Number of Circuits n	A=20 a=26db	A=40 a=32db	A=70 a=37db	A=100 a=40db	A=1000 a=60db	A=10^4 a=80db	A=10^5 a=100db
2(1 pair)	6.2	9.0	11.8	14.1	44.7	141.4	447.1
4(2 pair)	3.0	3.5	4.1	4.5	8.0	14.1	25.2
6(3 pair)	2.3	2.6	2.8	3.1	4.5	6.6	9.6
8(4 pair)	1.9	2.2	2.3	2.5	3.5	4.5	6.0
10(5 pair)	1.74	1.92	2.06	2.15	2.78	3.53	4.5

EXAMPLES

1. Given a t-r-f amplifier of one stage with input and output tuned circuits, each with a Q of 100; what is the bandwidth 20 db down at 1000 kc?

From the table, W= 3. We have then $f_w - Wf_\theta/Q =$ $3x1000/100 = 30$ kc.

2. Given an i-f amplifier with four circuits in two pairs, all tuned to 455 kc and having a Q of 90; what is the bandwidth at 40 db down?

From the table, W = 4.5. $f_w = Wf_o/Q = 4.5x455/90 = 22.7$ kc. The complete selectivity curve can be obtained by using the W's for other attenuations.

3. It is required that one pair of optimum-coupled i-f circuits have a bandwidth of 18 kc at 20 db down, operating at 455 kc; what Q is necessary?

$Q = Wf_o/f_w = 4.5x455/18 = 113.$

4. It is required that an amplifier have a bandwidth of 10 kc at 6 db and an attenuation of at least 60 db at a bandwidth of 60 kc; what circuit arrangement can be used, and what Q is required for operation at 455 kc?

In terms of bandwidths, $(f_w)60 \leqq 6(f_w)_6$, or $W_{60}f_o/Q \leqq 6\ W_6f_o/Q$, where the new subscripts indicate the attenuations in decibels. It is seen that f_o and Q cancel out, leaving the requirement,

$$\frac{W_{60}}{W_6} \leqq 6.$$

From the table we obtain:

Circuits	W_6	W_{60}	W_{60}/W_6
5 separate	0.57	3.9	6.8
6 separate	0.51	3.0	5.9
4 in pairs	1.4	8.0	5.7
6 in pairs	1.2	4.5	3.8

This shows that six separate circuits would be required; but four circuits in pairs are sufficient, and are chosen. The necessary Q is determined by the required 10-kc bandwidth at 6 db,
$Q= Wf_o/f_w = 1.4x455/10 = 64.$