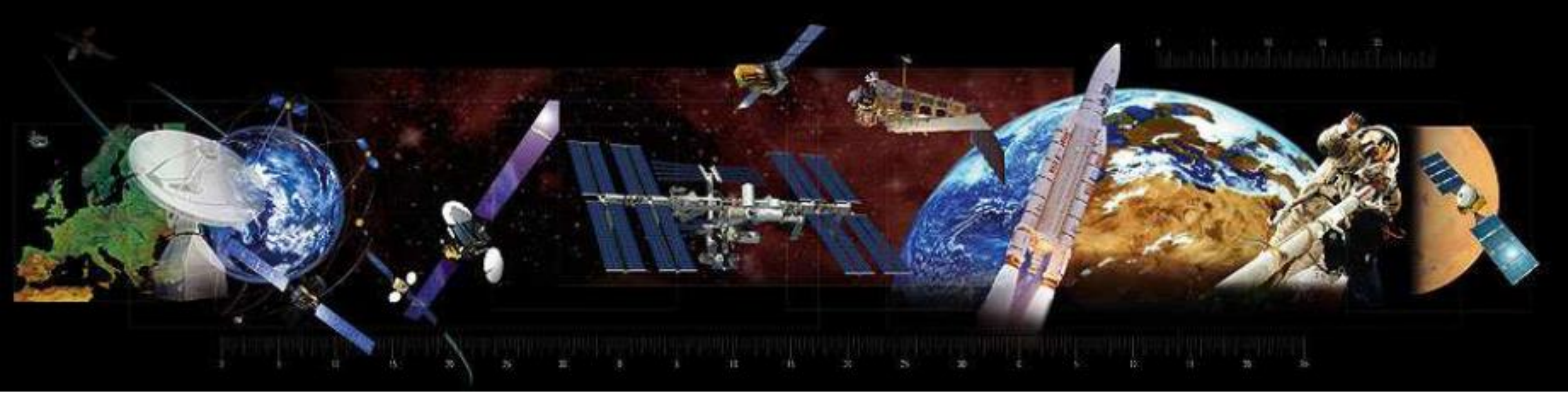

Multi-Section Symmetrical Directional Couplers

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Presentation Content

N-section Symmetrical Directional Couplers

1. Technical Articles on N-section Symmetrical Couplers.
2. Principle of Operation.
3. Terminology of Couplers.
4. Typical RF Performance Specs.
5. Application of Couplers.
6. Types of Symmetrical Couplers.
7. Physical Construction.
8. Bandwidth of Max-Flat Couplers.
9. 3-section Symmetrical Couplers:
    a. Max-Flat frequency response.
    b. Ripple: ± 0.3dB freq. response.
    c. 3dB coupling versus ripple.
10. 5-section Symmetrical Couplers:
    a. Max-Flat frequency response.
    b. Ripple: ± 0.3dB freq. response.
    c. 3dB coupling versus ripple.
11. 7-section Symmetrical Couplers:
    a. Max-Flat frequency response.
    b. Ripple: ± 0.3dB freq. response.
    c. 3dB coupling versus ripple.
12. 9-section Symmetrical Couplers:
    a. Max-Flat frequency response.
    b. Ripple: ± 0.3dB freq. response.
    c. 3dB coupling versus ripple.
13. Maximum usable frequency.
14. Insertion Loss in Couplers.
15. Degradation in Isolation: Phase.
16. Example: 9-section 10dB.
17. Example: 3-section 3dB.
18. Example: 3-section 6dB.
19. Asymmetrical vs. Symmetrical.
20. Summary.

Technical Articles

N-section Symmetrical Couplers & their realization in Stripline.

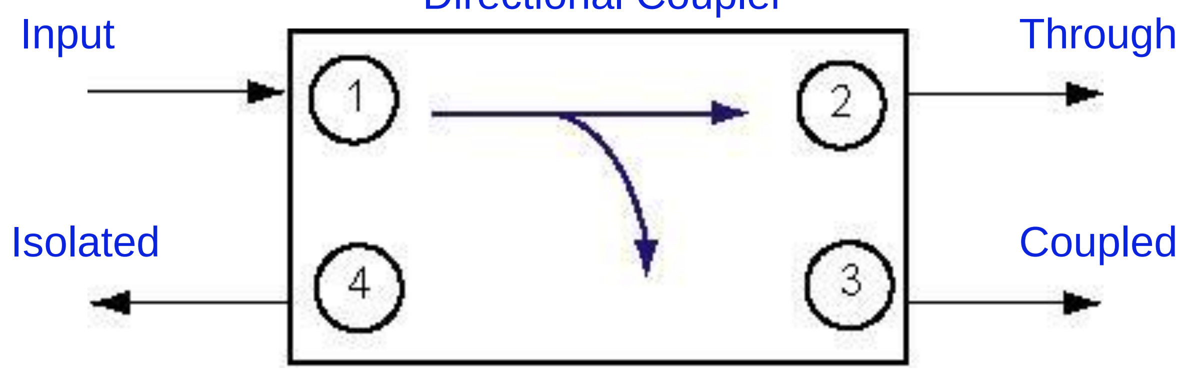
For Readers who wish to explore a more technical treatment of N-section symmetrical directional couplers and their physical realization in stripline:

1. E.G. Cristal, L. Young, "Theory and Tables of Optimum Symmetrical TEM-Mode Coupled Transmission-Line Directional Couplers", *IEEE Transactions on Microwave Theory and Tech.*, Volume 13, September 1965, pp. 693 - 695.
2. P. P. Toulious and A. C. Todd, "Synthesis of symmetrical TEM-mode Directional Couplers, " *IEEE Transactions on Microwave Theory and Techniques*, Volume 13, September 1965, pp. 536 thru 544.
3. Kammler, D.W.: 'The design of discrete N-section and continuously tapered symmetrical microwave TEM directional couplers', *IEEE Transactions on Microwave Theory and Techniques,* Volume MIT-17, 1969, pp. 577 thru 590.
4. Shelton, J. P., "Impedances of offset parallel-coupled strip transmission lines," *IEEE Transactions on Microwave Theory and Techniques,* Volume 14, No. 1, 1966, pp. 1338 thru 1341.
5. Bahl I. J., and Bhartia P., "The Design of Broadside-Coupled Stripline Circuits," *IEEE Transactions on Microwave Theory and Techniques,* Volume 29, No. 2, February 1981, pp. 165 thru 168.

Directional Coupler: Principle of Operation

One specific class of RF power divider is the directional coupler. This is a four-port device that samples the RF power flowing into Port 1, coupled into Port 3 (the coupled port), with the remainder of the RF power delivered to Port 2 (the through port) and (ideally) no RF power delivered to the isolated port (Port 4).

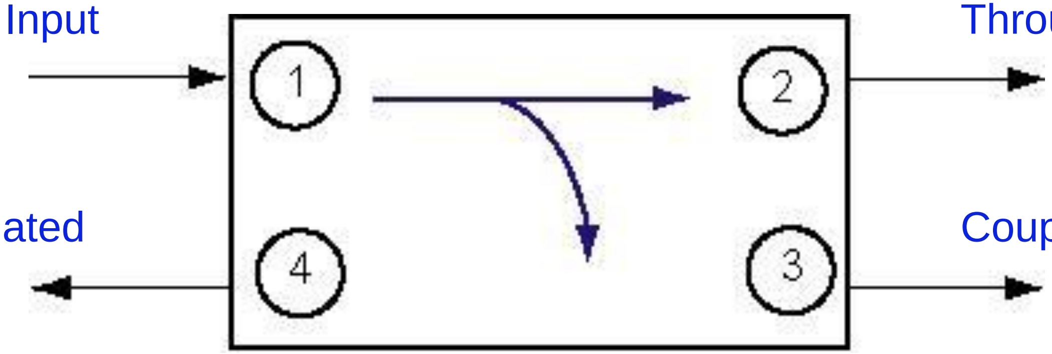
Block Diagram of a Directional Coupler



Usually the isolated port is terminated within the coupler's housing. In such case, the coupler appears to be a three port device. In the ideal case, no RF power is delivered to Port 4 (the isolated port).

Directional Coupler: Principle of Operation

Block Diagram of a Directional Coupler



$$T = 10\log\left(\frac{P_1}{P_2}\right)$$

$$I = 10\log\left(\frac{P_1}{P_4}\right)$$

$$C = 10\log\left(\frac{P_1}{P_3}\right)$$

Directional couplers are described by three key RF specifications:

1. **Coupling (C)**: The ratio of RF input power to the coupled RF power.
2. **Directivity (D):** The ratio of coupled RF power to the RF power at the isolated port. $D = 10\log\left(\frac{P_3}{P_4}\right)$
3. **Isolation (I)**: The ratio of RF input power to RF power out of the isolated port. $I = D + C,\ dB$

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Terminology for Directional Couplers

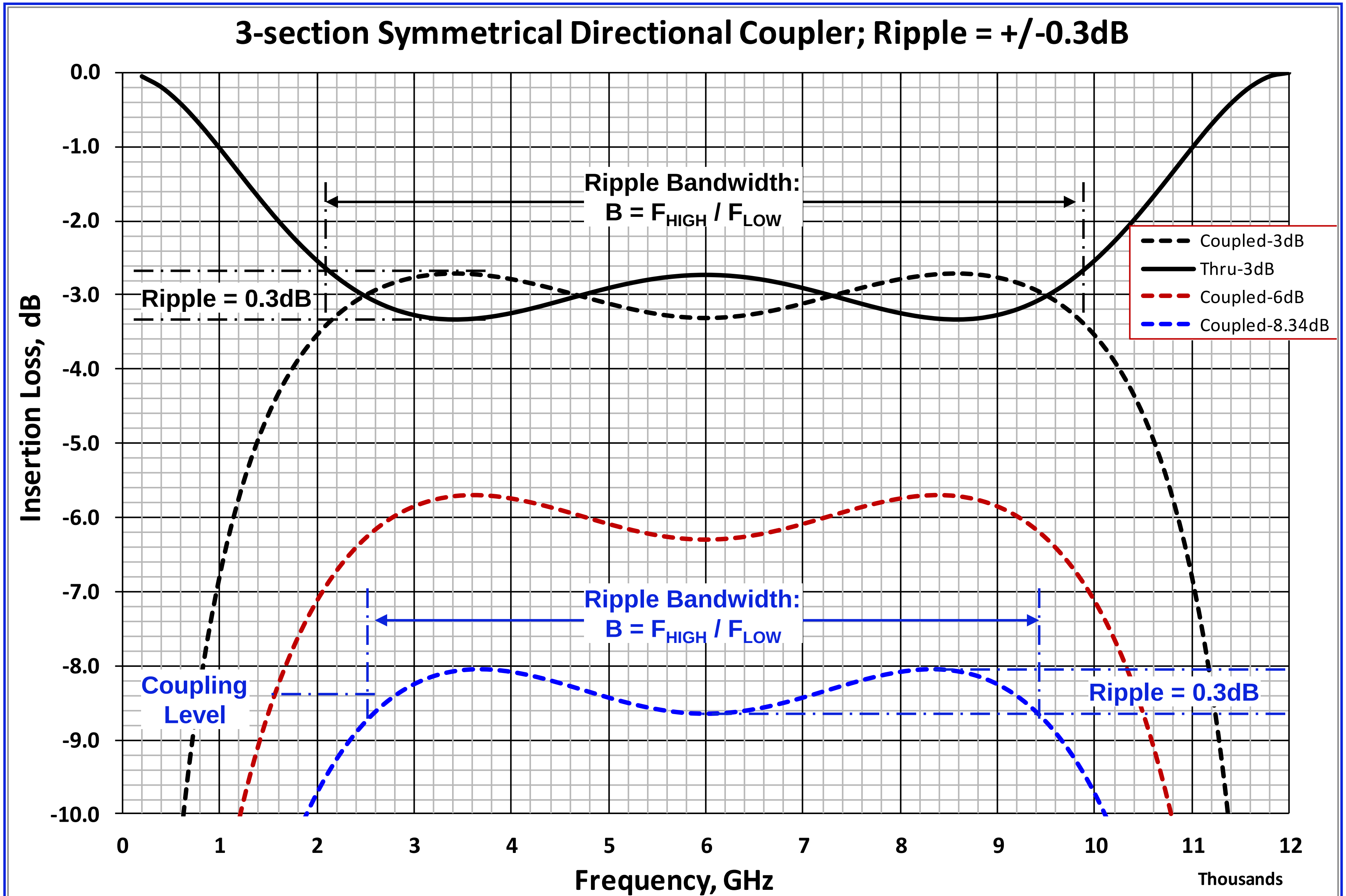
RF Performance Parameters

RF performance parameters that apply to directional couplers:

1. **Frequency Range:** The operating frequency range where RF specifications are guaranteed for the particular coupler.
2. **VSWR:** Voltage Standing Wave Ratio (VSWR) is a measure of the impedance of a coupler, relative to Zo ; often Zo = 50 ohms.
3. **Coupling:** Attenuation of the RF signal measured at the coupled port relative to the input RF signal level entering the coupler.
4. **Coupling Flatness:** Variation in coupling over the frequency range.
5. **Amplitude Balance:** The difference in attenuation between two or more output signals fed from a common input; generally expressed as a maximum variation in amplitude balance. Sometimes called: 'Amplitude Tracking'.
6. **Phase Balance**: The difference in electrical phase between two or more output signals fed from a common input, generally expressed as a maximum variation relative to the nominal phase difference between the two paths.
7. **Main Line Loss:** Total insertion loss thru the main line: Thru Path.
8. **Directivity:** RF signal level measured at an isolated port relative to the RF signal level measured at a coupled port, when the RF signal enters the RF input port.

Definition of Parameters: Ripple Bandwidth

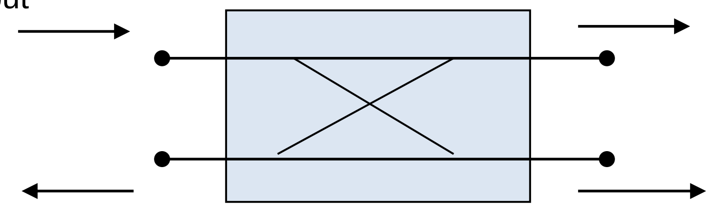
Example: 3-section Symmetrical Directional Coupler



Typical RF Performance Specifications for commercially-available 3dB Directional Couplers

3dB Couplers from 'Company A'

Frequency Range (GHz)	Amplitude Balance (dB)	Phase Imbalance (Degrees)	Minimum Isolation (dB)	Maximum VSWR	Insertion Loss (dB, Max)
0.5 to 7	± 0.4	± 5	19	1.30	1.3
2 to 8	± 0.35	± 3	19	1.25	0.65
1 to 12.4	± 0.4	± 7	20	1.30	1.4
2 to 18	± 0.4	± 7	17	1.35	1.4
1 to 18	± 0.5	± 10	17	1.35	2.0
6 to 20	± 0.4	± 5	14	1.40	1.0
10 to 40	± 0.75	± 10	13	1.80	1.8



Functional Diagram of a 3dB Directional Coupler

3dB Couplers from 'Company B'

Frequency Range (GHz)	Amplitude Balance (dB)	Insertion Loss (dB, Max)	Minimum Isolation (dB)	Maximum VSWR
1.0 to 2.0	± 0.5	0.20	22	1.20
2.0 to 4.0	± 0.5	0.25	22	1.25
4.0 to 8.0	± 0.5	0.30	20	1.25
8.0 to 12.4	± 0.5	0.50	18	1.35
12.4 to 18	± 0.5	0.50	18	1.45
0.5 to 2.0	± 0.5	0.60	24	1.20
2.0 to 8.0	± 0.5	0.50	20	1.30
4.0 to 12.4	± 0.5	0.60	20	1.25
2.0 to 18.0	± 1	0.60	20	1.45
6.5 to 18.0	± 0.5	0.60	18	1.35
4.0 to 18.0	± 0.5	1.0	18	1.45

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Typical RF Performance Specifications for commercially-available Directional Couplers

Commercially-available Directional Couplers: 1 to 12.4 GHz

Frequency Range (GHz)	Nominal Coupling (dB)	Directivity (dB)		Insertion Loss		VSWR		Frequency Sensitivity (dB)	Max Deviation from Nominal (dB)
		1- 8 GHz	8 - 12.4 GHz	Excluding Coupled Power (dB)	True Loss (Max)	Primary Line (Max)	Secondary Line (Max)		
1 to 12.4	6	15	12	0.7	2.35	1.35	1.50	± 0.5	± 1.0
1 to 12.4	10	15	12	0.7	1.30	1.35	1.50	± 0.5	± 1.5
1 to 12.4	20	15	15	0.7	0.75	1.35	1.50	± 0.5	± 1.5

Commercially-available Directional Couplers: 2 to 18 GHz

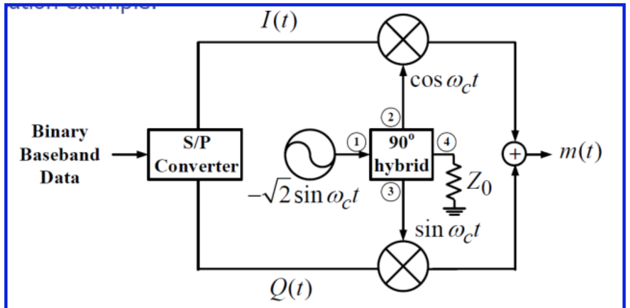
Frequency Range (GHz)	Nominal Coupling (dB)	Directivity (dB)		Insertion Loss		VSWR		Frequency Sensitivity (dB)	Max Deviation from Nominal (dB)
		2 - 12.4	12.4 - 18	Excluding Coupled Power (dB)	True Loss (Max)	Primary Line (Max)	Secondary Line (Max)		
2 to 18 GHz	6	15	12	0.90	2.0	1.40	1.40	± 0.5	± 1.0
2 to 18 GHz	10	15	12	0.90	1.4	1.35	1.50	± 0.5	± 1.0
2 to 18 GHz	16	15	12	0.65	0.8	1.35	1.40	± 0.5	± 1.0

Application of N-section Symmetrical Couplers

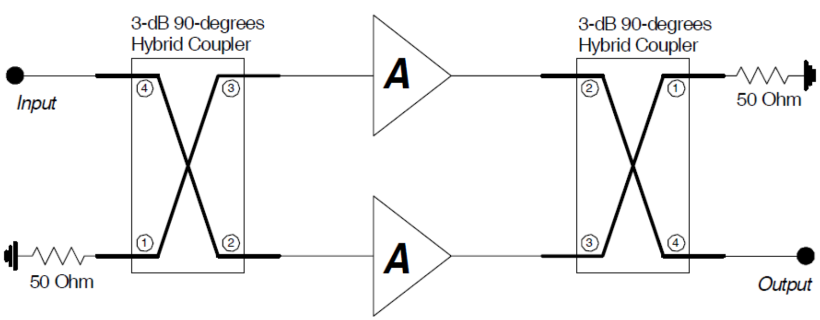
In RF circuits and systems; N = Odd number of coupled sections

N-section symmetrical directional couplers provide broad bandwidth frequency operation which finds use in lots of RF circuits and systems:

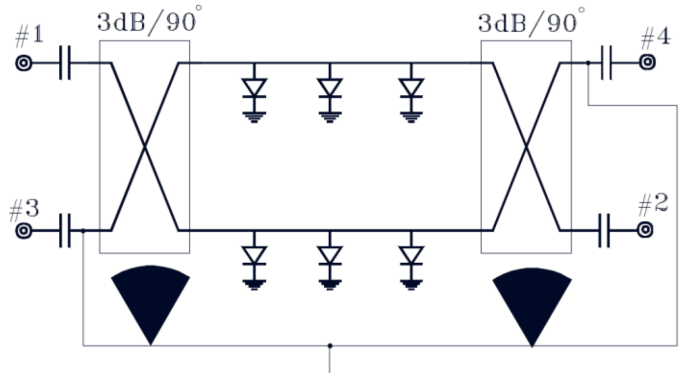
1. Beamforming Networks for Passive Phased Array Antennas.
2. Butler Matrices for combining multiple power amplifiers.
3. Balanced high RF power amplifier circuits.
4. Non-reflective PIN-diode Variable Attenuators and DPDT RF Switches.
5. Quadrature Modulators for QPSK RF circuits.
6. RF power monitors using crystal and diode detectors.
7. Any many other RF circuits and systems. . . . .



Quadrature Modulator

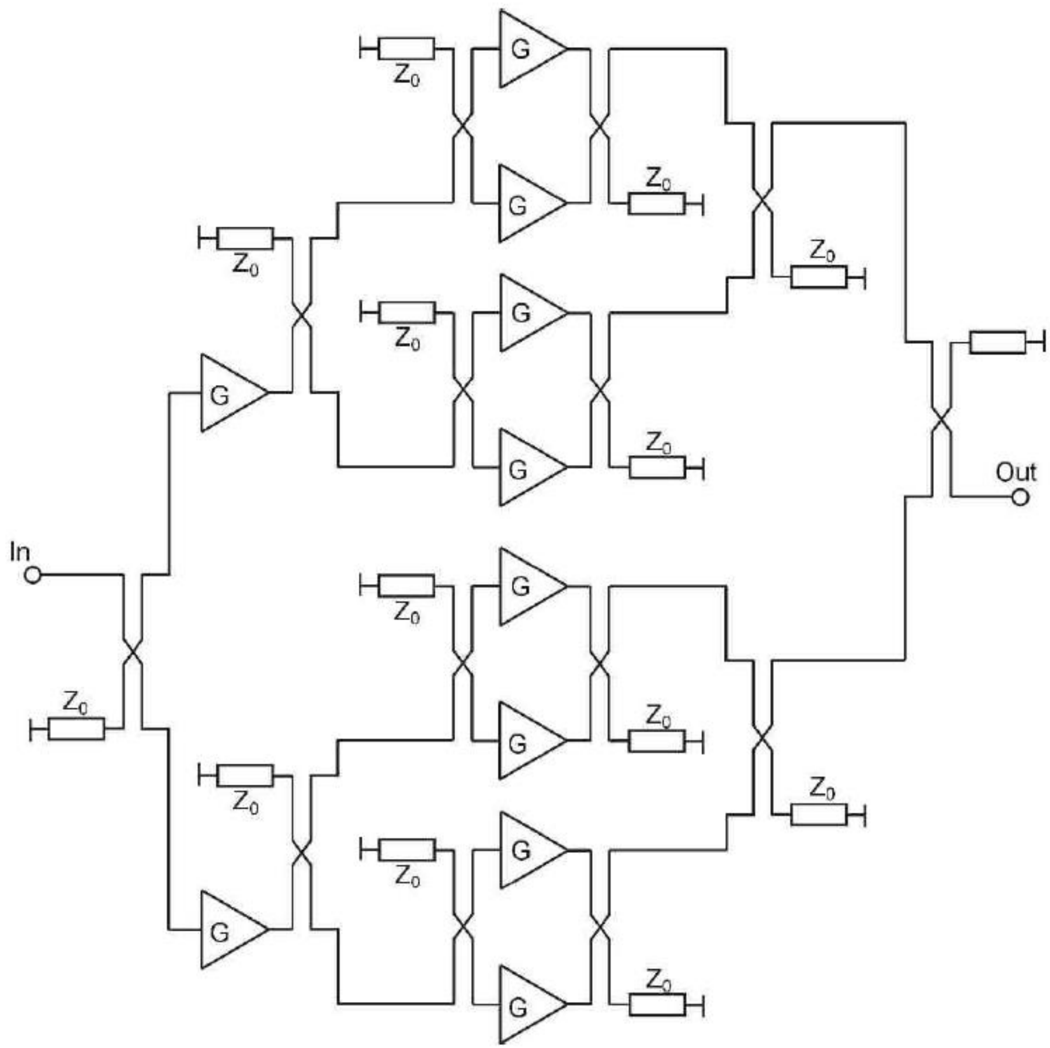


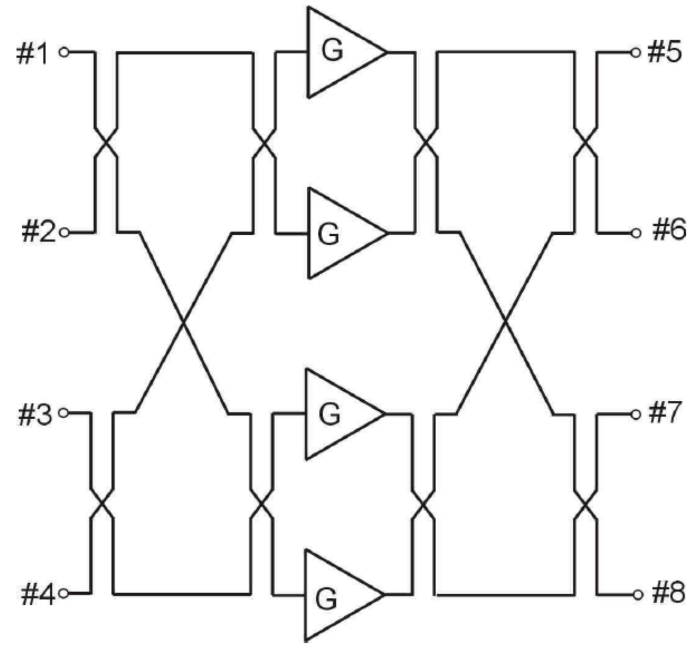
Balanced amplifier constructed with 3dB hybrid couplers.



PIN-diode non-reflective Variable Attenuator

Application: Power Amplifiers using many multi-section 3dB quadrature Directional Couplers





Schematic diagram of a four-channel amplifier.

Schematic diagram of an 8-way power amplifier.

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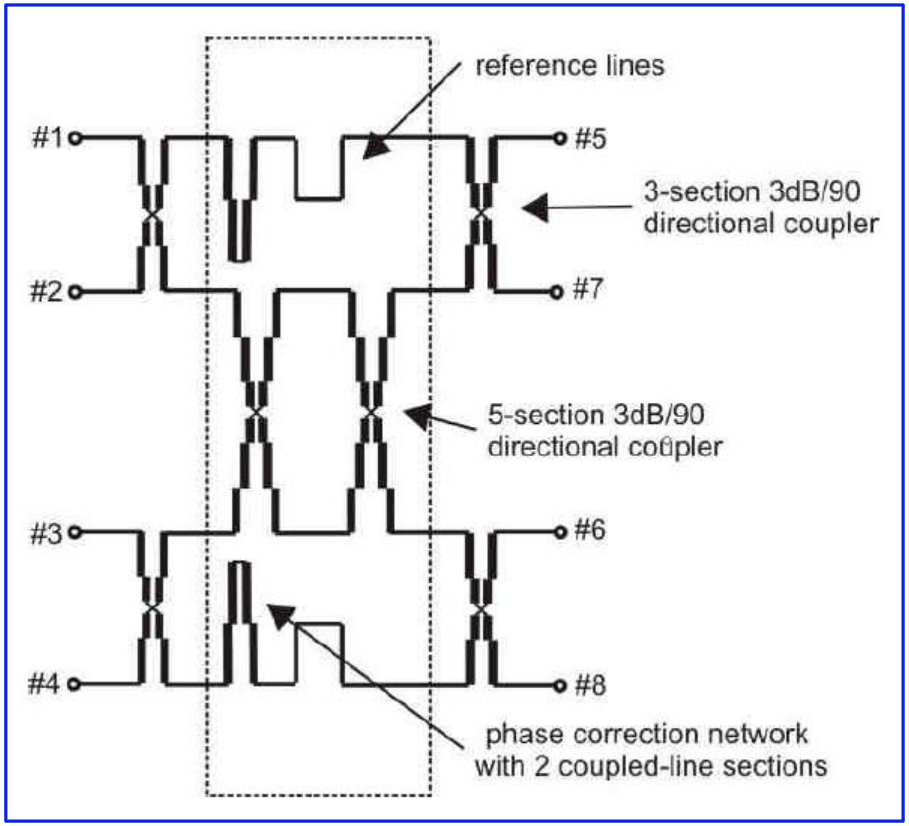
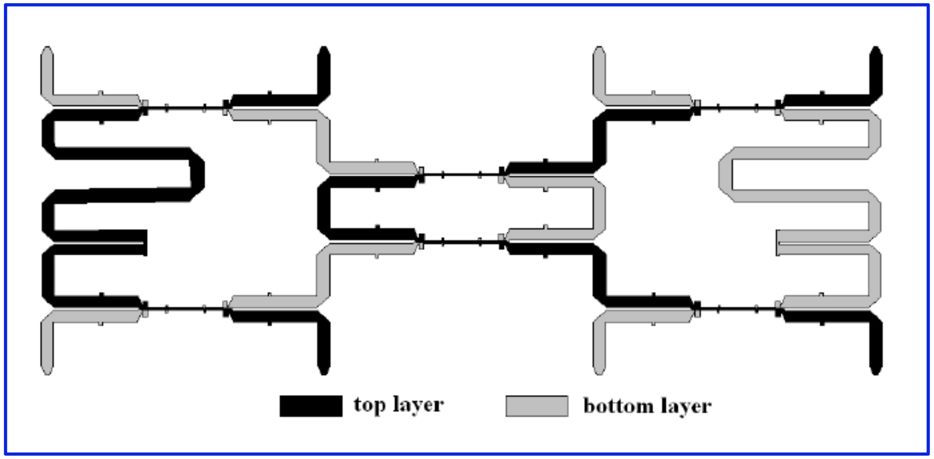
Application: Multi-section 3dB Directional Couplers used in a 4 x 4 Butler Matrix



A broadband 4 x 4 Butler matrix consisting of 3-section symmetrical coupled-line directional couplers. The middle network consists of a tandem connection of two 5-section symmetrical 3-dB/90° coupled-line directional couplers, two 2-section coupled-line phase correction networks and reference lines.

Butler matrices are used in a broad range of applications in modern-day communications:

1. Beamforming networks for multi-beam Antennas.
2. Direction finding systems.
3. Multi-channel amplifiers.



Layout of the designed broadband 4 x 4 Butler matrix consisting of six three-section symmetrical 3-dB/90° coupled-line directional couplers, two 'C'-sections of coupled-lines and reference lines

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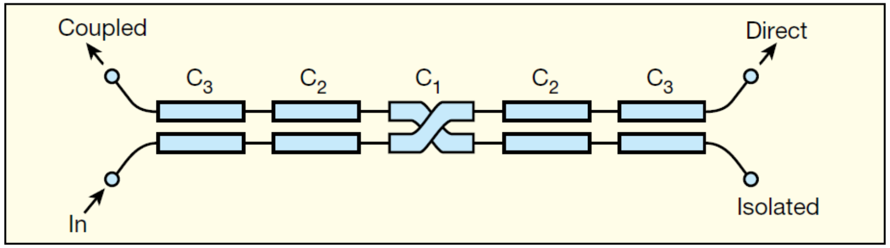
Types of Symmetrical Directional Couplers

With & without crossover; Tandem couplers

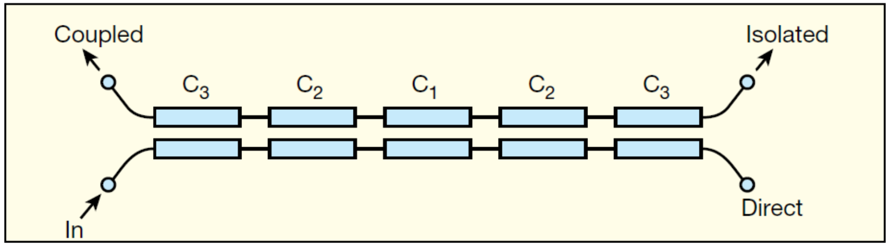
Symmetrical directional couplers are often realized and constructed as:

1. Symmetrical coupler with center strips that crossover at the coupler's center coupled section.
2. Symmetrical coupler with center strips that do not crossover at the coupler's center coupled section.
3. Tandem connection of two 8.34dB multi-section symmetrical couplers to realize a 3dB coupler, with cross-over at each center coupled section.

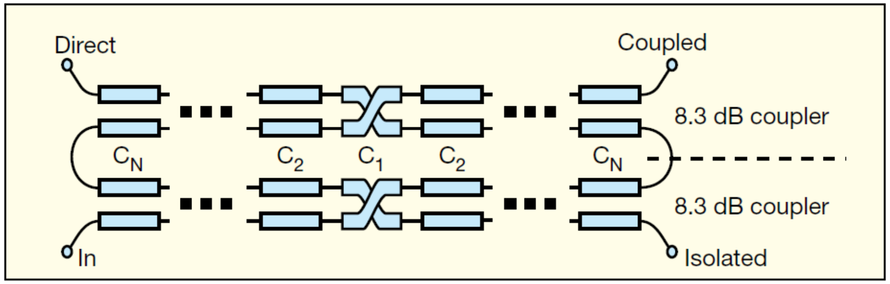
The type of N-section symmetrical coupler best suited for your application is often decided based on where the RF coupled port and thru port are located to interconnect to neighboring RF circuit structures/components.



1. This simple diagram shows a symmetrical five-multisection coupler with a crossover.



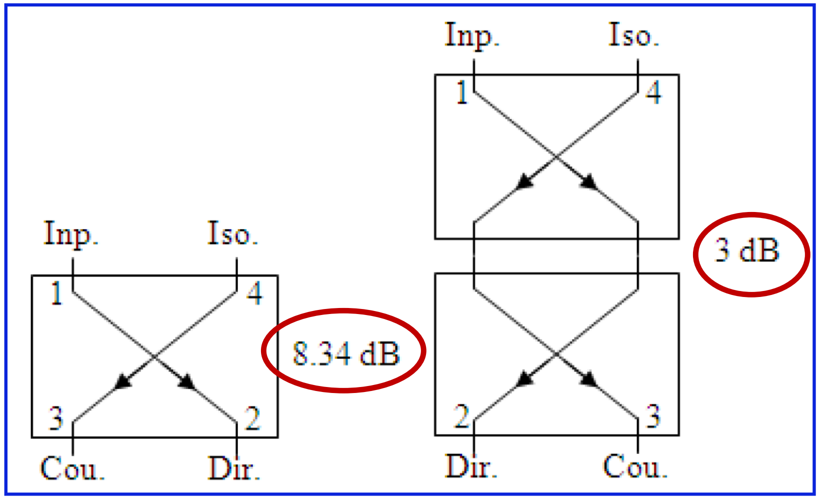
2. This diagram illustrates a symmetrical five-multisection coupler without a crossover.



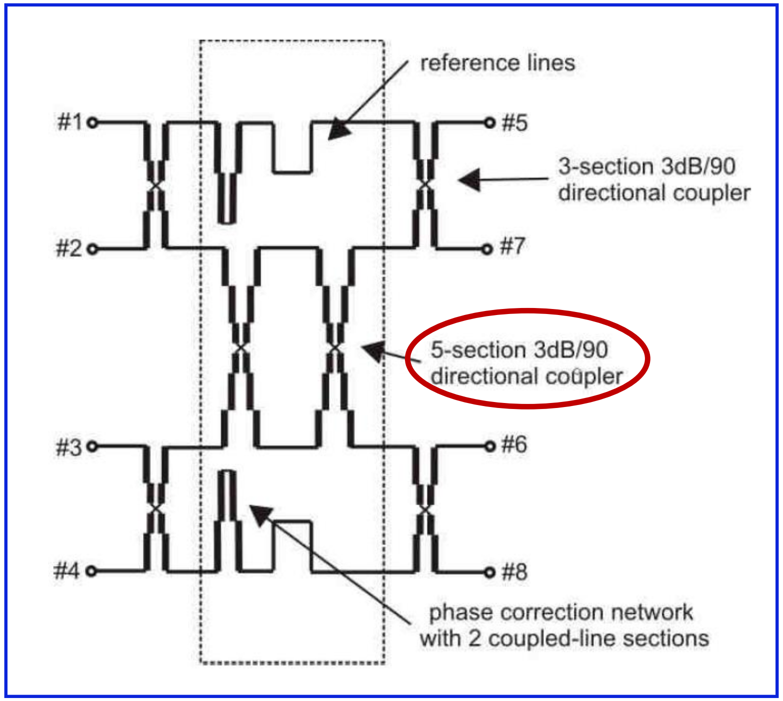
3. This diagram shows the tandem connection of two 8.3-dB multisection couplers.

Example: Tandem 3dB Couplers

Using N-section Symmetrical 8.34dB Directional Couplers



Use of two 'loosely-coupled' 8.34dB couplers to realize a 3dB coupler.



Tandem 5-section 8.34dB couplers used to realize a 3dB coupler.

Note: It can be shown that **three tandem 11.74dB** N-section symmetrical couplers can be used to realize a 3dB coupler. The physical dimensions of each 11.74dB coupler are more readily realized than the 'stronger' 8.34dB symmetrical coupler.

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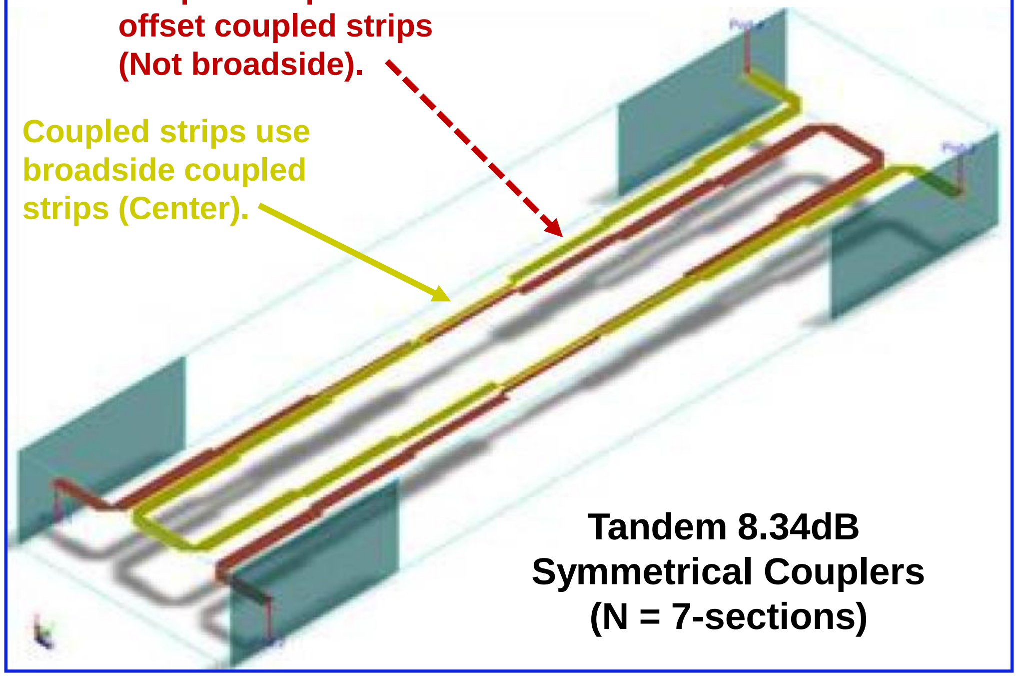
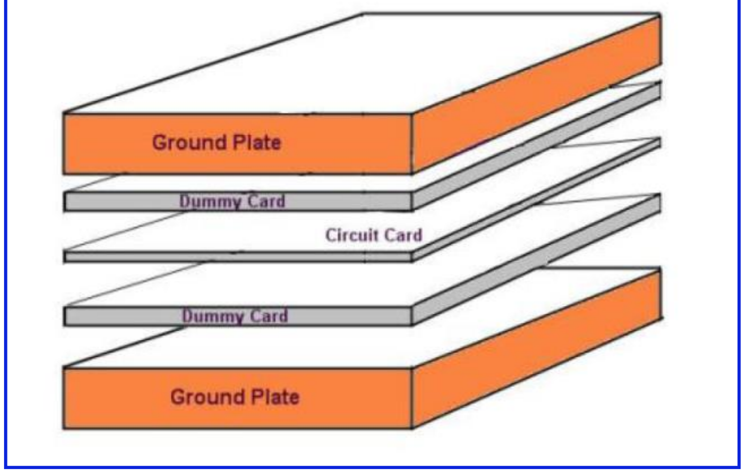
Physical Construction of Stripline Couplers

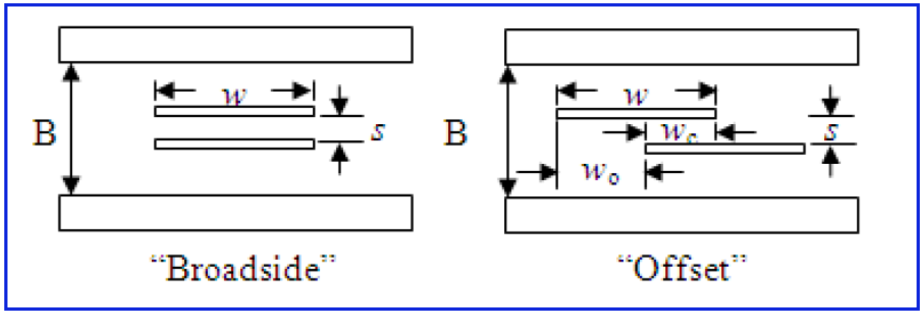
Using Parallel-Coupled Strips: Broadside Strips & Offset Strips



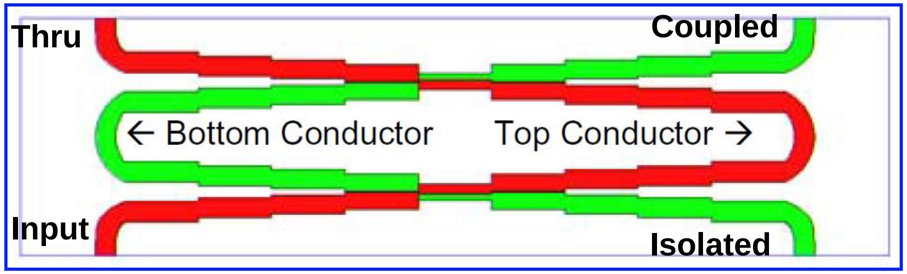
Tandem 8.34dB Symmetrical Couplers (N = 7-sections)



Physical construction of stripline couplers using 3 dielectric layers.



Cross-section to realize Stripline Couplers



Tandem 8.34dB Symmetrical Couplers

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Bandwidth of Maximally-Flat Symmetrical Couplers

3dB Operating Bandwidth versus 0.1dB Operating Bandwidth

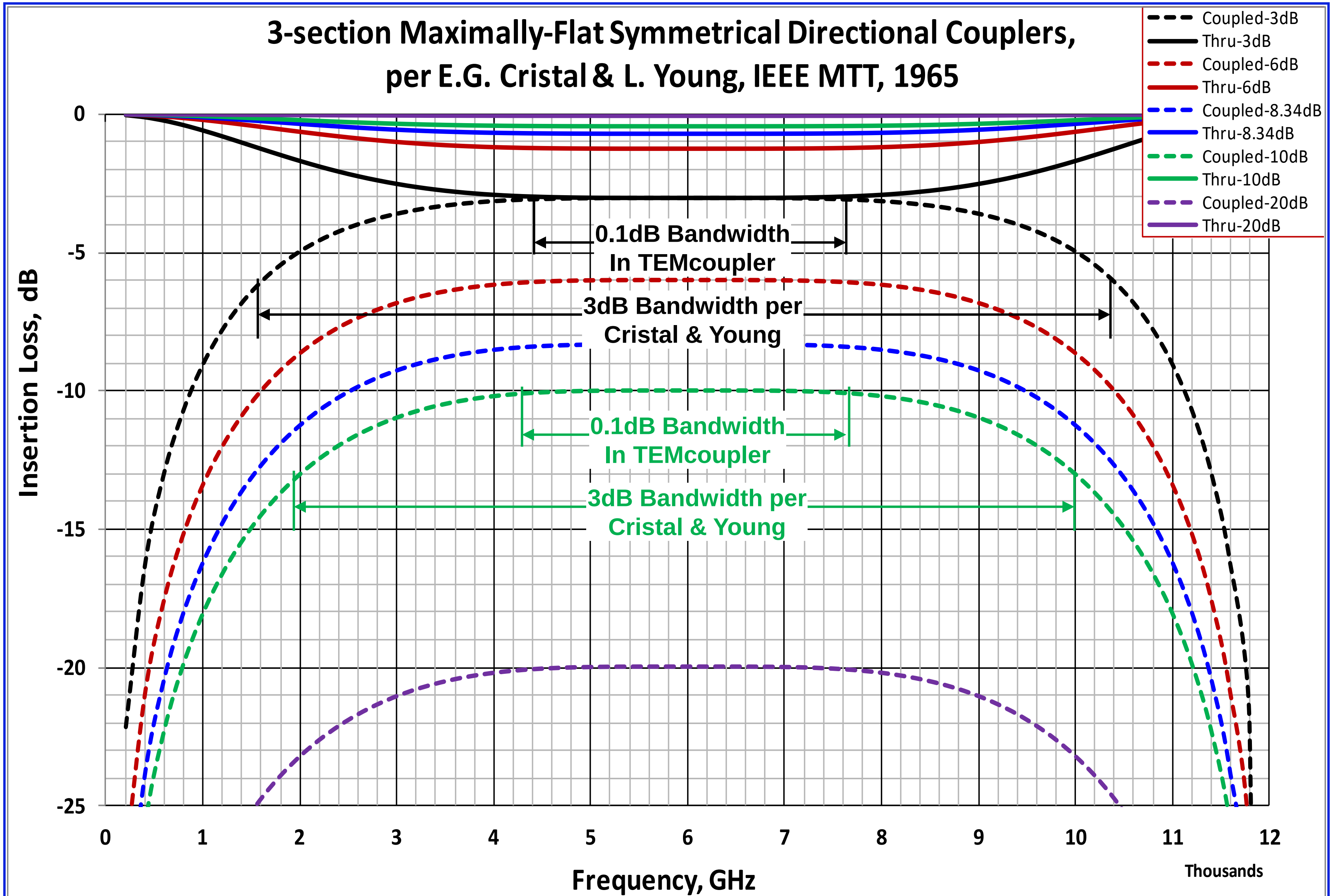
The operating bandwidth of a Maximally-Flat Symmetrical Coupler covers the frequency range where the amplitude of the coupled & thru RF path is ‘flat’ and, therefore, produces little/no amplitude ripple across those frequencies. In their technical article, Cristal & Young report the operating bandwidth of their maximally-flat symmetrical couplers as the frequency range where the amplitude is 3dB lower then the mean coupling:

> *‘In the cases of maximally-flat coupler designs (Tables A-21 to A-24), the frequencies f_2 and f_1 used in the formulas for bandwidth refer to the frequencies that are 3dB lower than the mean coupling.’*

Cristal & Young’s 3dB bandwidth definition for maximally-flat couplers results in a bandwidth ratio: B = f_2 / f_1 which is ‘huge’, and approaches the bandwidth ratio of a 7-section symmetrical coupler.

To ‘level the playing field’, Atlanta RF’s CAE software product: TEMcoupler defines the operating bandwidth for all maximally-flat symmetrical couplers as the frequency points where the amplitude is at/near *0.1dB lower than the mean coupling* value. This approach significantly reduces the bandwidth ratio, but produces a design consistent with the ripple bandwidth of all other symmetrical coupler designs and is more realistic.

Bandwidth of Maximally-Flat Symmetrical Couplers
Cristal/Young's 3dB Bandwidth vs 0.1dB Bandwidth in TEMcoupler



3-section Symmetrical Directional Couplers

Fractional Bandwidth versus Amplitude Ripple

Fractional Bandwidth vs Amplitude Ripple for a 3-section Symmetrical 3.01 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.53333	1.72727
0.10	1.00760	3.03063
0.20	1.17199	3.83085
0.30	1.27572	4.52271
0.40	1.35225	5.17521
0.50	1.41305	5.81489
0.60	1.46353	6.45616

Fractional Bandwidth vs Amplitude Ripple for a 3-section Symmetrical 6.02 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.60000	1.85714
0.10	0.91996	2.70356
0.20	1.07404	3.31984
0.30	1.17223	3.83226
0.40	1.24519	4.29931
0.50	1.30345	4.74258
0.60	1.35201	5.17291

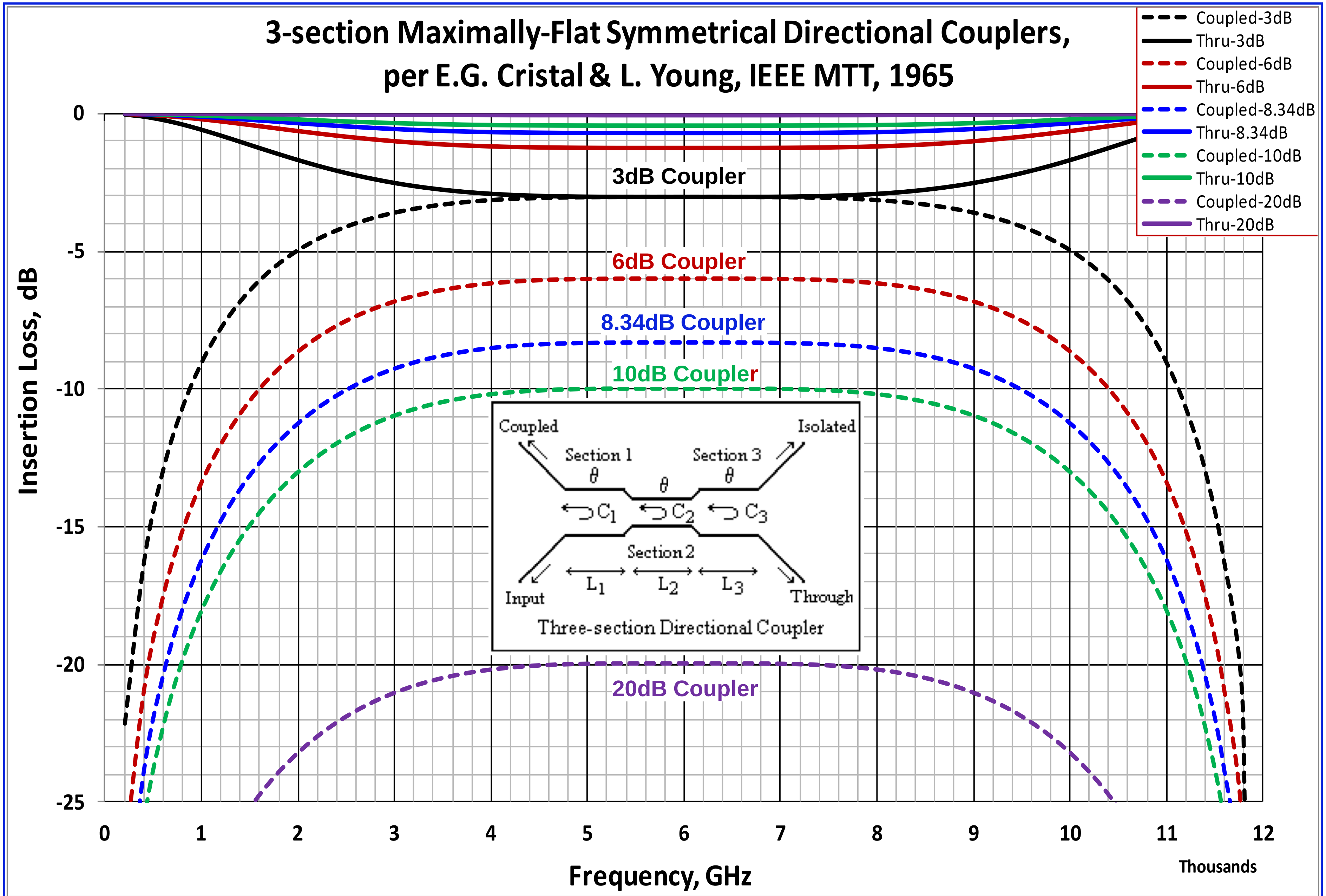
Fractional Bandwidth vs Amplitude Ripple for a 3-section Symmetrical 8.34 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.70000	2.07692
0.10	0.89286	2.61290
0.20	1.04355	3.18211
0.30	1.13986	3.65041
0.40	1.21159	4.07347
0.50	1.26898	4.47178
0.60	1.31686	4.85550

Fractional Bandwidth vs Amplitude Ripple for a 3-section Symmetrical 10.0 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.60000	1.84337
0.10	0.94802	2.70026
0.20	1.03140	3.12968
0.30	1.11478	3.55910
0.40	1.19816	3.98852
0.50	1.26757	4.48776
0.60	1.30228	4.73738

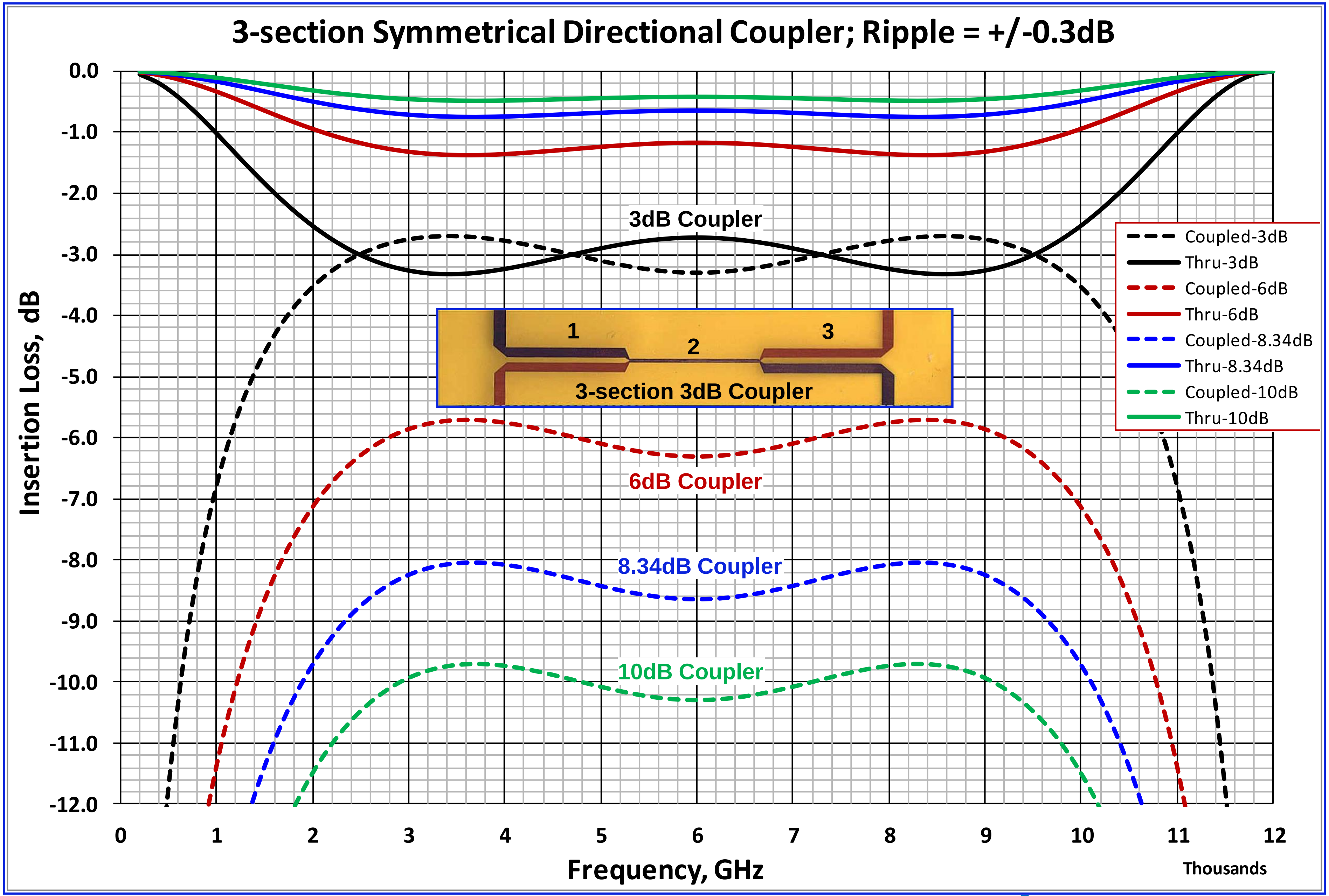
where:

FBW = Fractional Bandwidth = $(f_{high} - f_{Low})/f_o$

Ration = f_{high}/f_{low} = Bandwidth Ratio.



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

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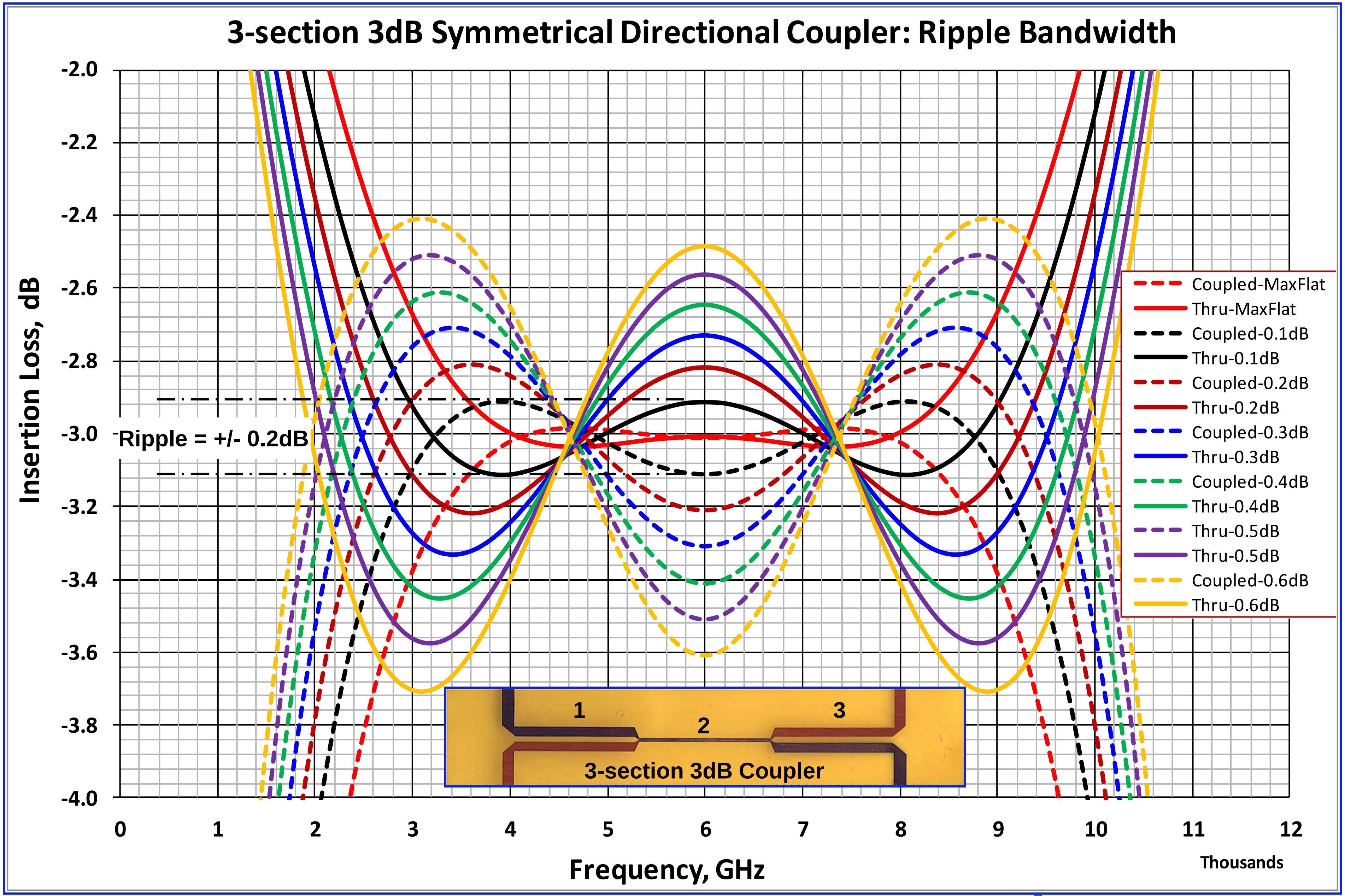

Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

5-section Symmetrical Directional Couplers
Fractional Bandwidth versus Amplitude Ripple

Fractional Bandwidth vs Amplitude Ripple for a 5-section Symmetrical 3.01 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.80000	2.33333
0.10	1.32559	4.93114
0.20	1.45184	6.29714
0.30	1.52744	7.46462
0.40	1.58152	8.55845
0.50	1.62357	9.62609
0.60	1.65791	10.69292

Fractional Bandwidth vs Amplitude Ripple for a 5-section Symmetrical 6.02 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.83333	2.42857
0.10	1.25446	4.34522
0.20	1.37766	5.42738
0.30	1.45202	6.29953
0.40	1.50548	7.08866
0.50	1.54720	7.83386
0.60	1.58135	8.55462

Fractional Bandwidth vs Amplitude Ripple for a 5-section Symmetrical 8.34 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	1.06666	3.28600
0.10	1.23184	4.20727
0.20	1.35395	5.19150
0.30	1.42783	5.99090
0.40	1.48104	6.70767
0.50	1.52262	7.37898
0.60	1.55670	8.02323

Fractional Bandwidth vs Amplitude Ripple for a 5-section Symmetrical 10.0 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.76667	2.24324
0.10	1.28104	4.37019
0.20	1.34442	5.10148
0.30	1.40780	5.83278
0.40	1.47118	6.56407
0.50	1.52156	7.40478
0.60	1.54675	7.82513

where:

FBW = Fractional Bandwidth = $(f_{high} - f_{Low})/f_o$

Ration = f_{high}/f_{low} = Bandwidth Ratio.

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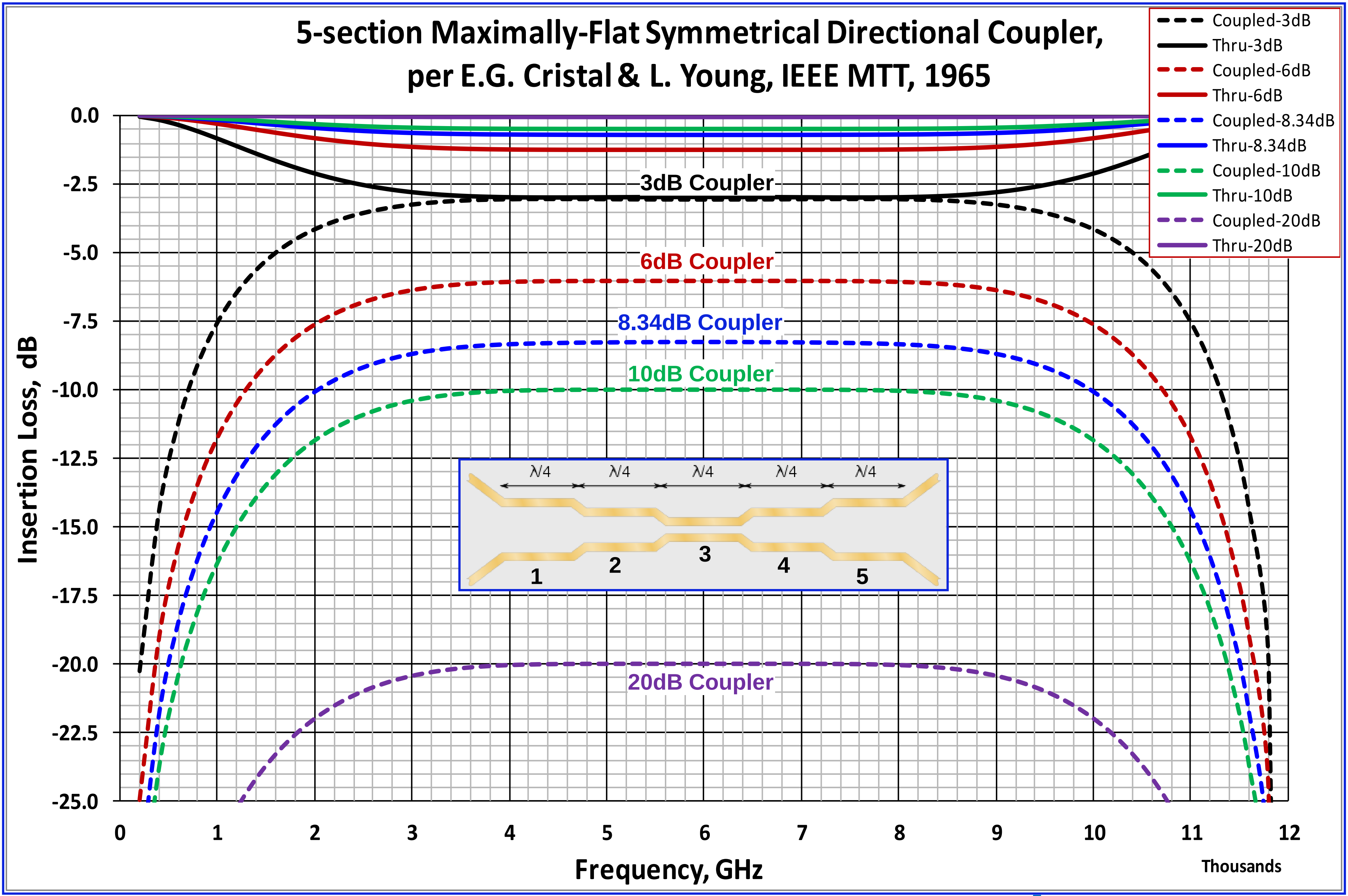

Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

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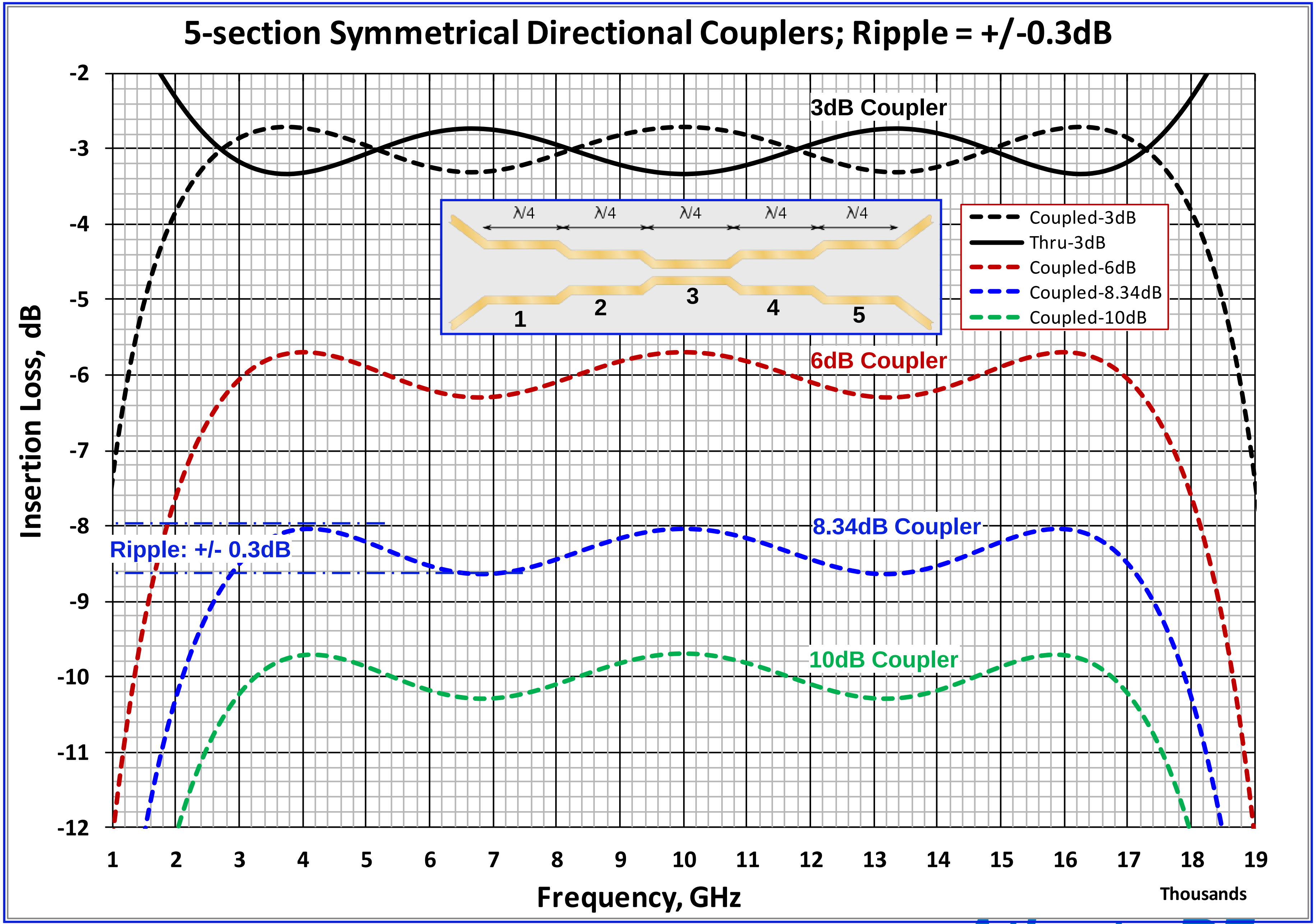
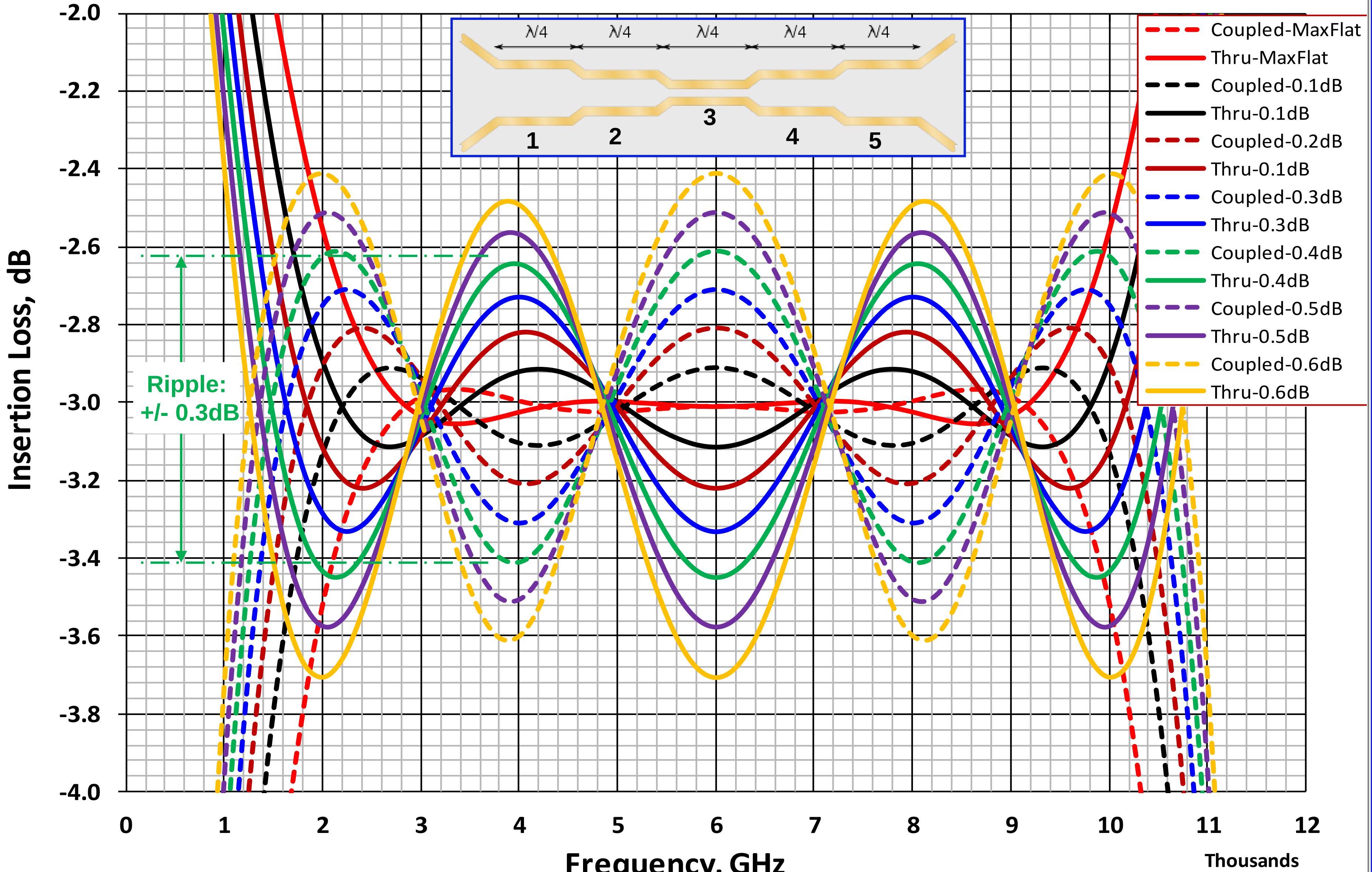


Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

5-section 3dB Symmetrical Directional Coupler: Ripple Bandwidth



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

7-section Symmetrical Directional Couplers

Fractional Bandwidth versus Amplitude Ripple

Fractional Bandwidth vs Amplitude Ripple for a 7-section Symmetrical 3.01 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.90000	2.63636
0.10	1.49705	6.95310
0.20	1.59539	8.88600
0.30	1.65308	10.5302
0.40	1.69388	12.0666
0.50	1.72534	13.5637
0.60	1.75090	15.0578

Fractional Bandwidth vs Amplitude Ripple for a 7-section Symmetrical 6.02 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.93333	2.75000
0.10	1.44052	6.1494
0.20	1.53802	7.65830
0.30	1.59558	8.8908
0.40	1.63645	10.0026
0.50	1.66806	11.0505
0.60	1.69378	12.0626

Fractional Bandwidth vs Amplitude Ripple for a 7-section Symmetrical 8.34 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	1.28333	4.58130
0.10	1.42127	5.91170
0.20	1.51889	7.31400
0.30	1.57653	8.44580
0.40	1.61749	9.45720
0.50	1.64919	10.4022
0.60	1.67500	11.3077

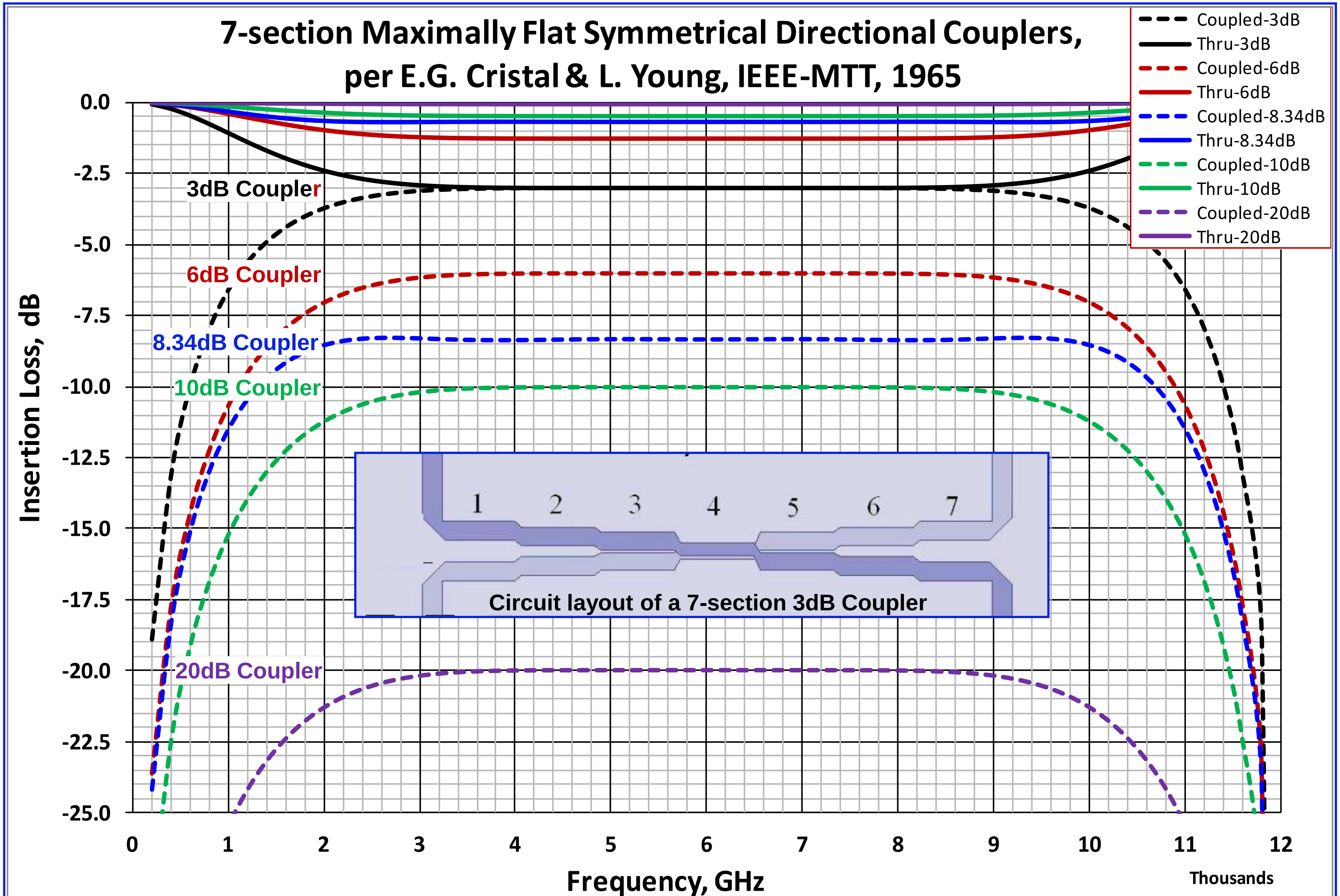
Fractional Bandwidth vs Amplitude Ripple for a 7-section Symmetrical 10.0 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	0.93333	2.75000
0.10	1.40202	5.67400
0.20	1.51198	7.19650
0.30	1.56113	8.23015
0.40	1.61028	9.26380
0.50	1.64858	10.4468
0.60	1.66773	11.0383

where:

FBW = Fractional Bandwidth = $(f_{high} - f_{Low})/f_o$

Ration = f_{high}/f_{low} = Bandwidth Ratio.

7-section Maximally Flat Symmetrical Directional Couplers, per E.G. Cristal & L. Young, IEEE-MTT, 1965



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

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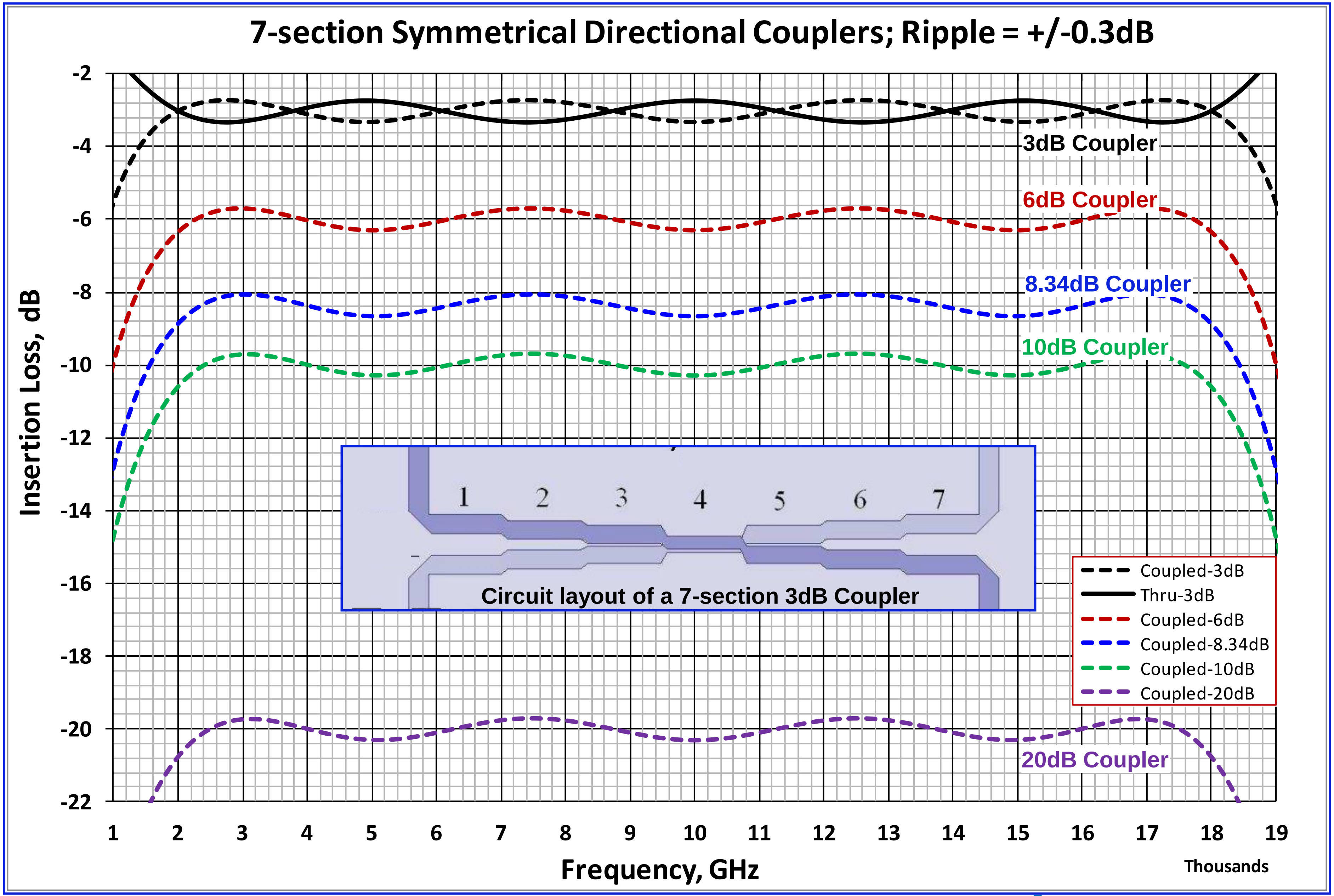
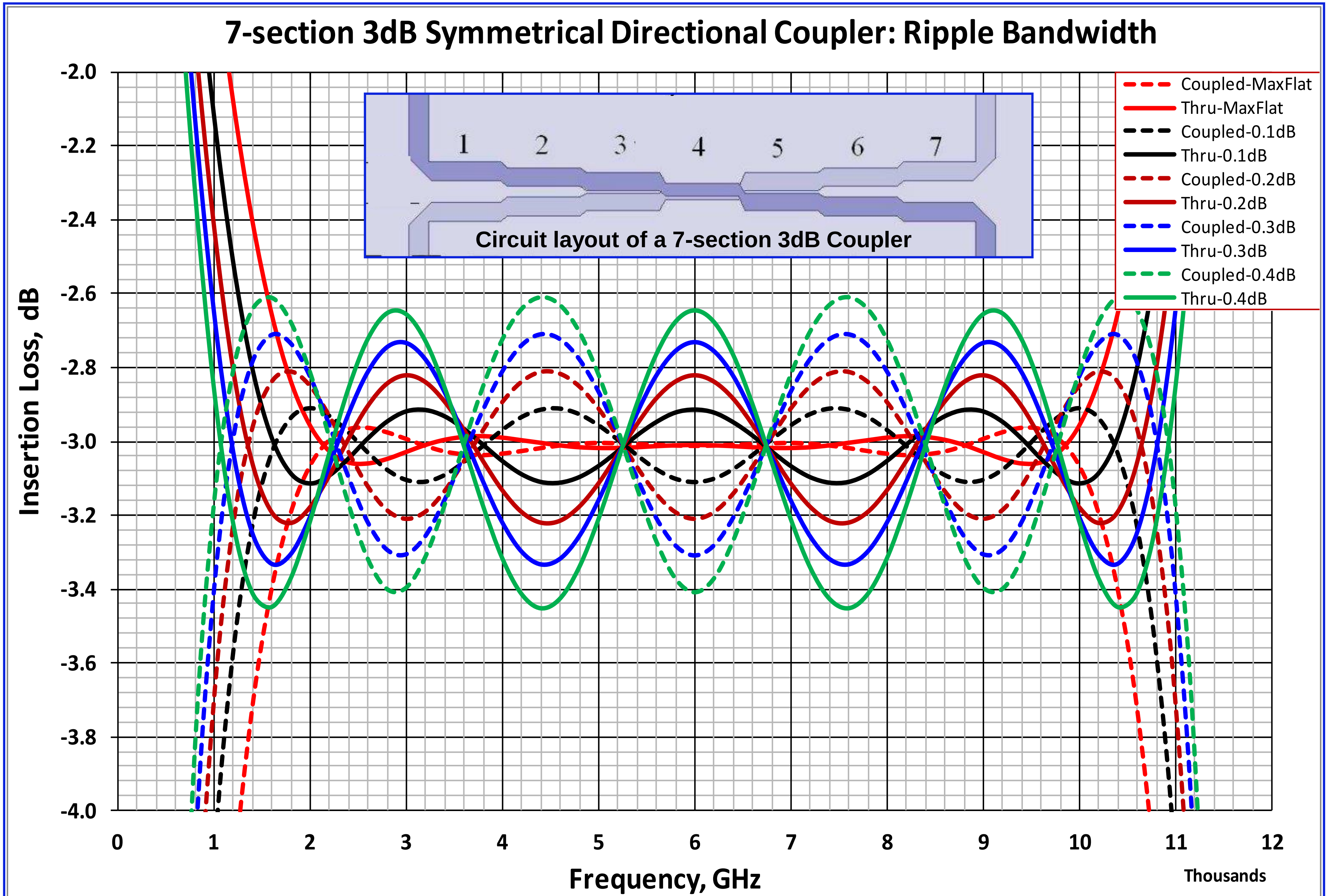


Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

9-section Symmetrical Directional Couplers
Fractional Bandwidth versus Amplitude Ripple

Fractional Bandwidth vs Amplitude Ripple for a 9-section Symmetrical 3.01 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	1.016666	3.0673
0.10	1.60120	9.03000
0.20	1.68070	11.5280
0.30	1.72690	13.6490
0.40	1.75940	15.6270
0.50	1.78440	17.5540
0.60	1.80460	19.4750

Fractional Bandwidth vs Amplitude Ripple for a 9-section Symmetrical 6.02 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	1.05000	3.21053
0.10	1.55500	7.98900
0.20	1.63450	9.94300
0.30	1.68090	11.5350
0.40	1.71360	12.9690
0.50	1.73890	14.3190
0.60	1.75940	15.6220

Fractional Bandwidth vs Amplitude Ripple for a 9-section Symmetrical 8.34 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	1.43333	6.0588
0.10	1.53920	7.6810
0.20	1.61900	9.4980
0.30	1.66560	10.960
0.40	1.69850	12.265
0.50	1.72380	13.484
0.60	1.74440	14.650

Fractional Bandwidth vs Amplitude Ripple for a 9-section Symmetrical 10.0 dB Coupler		
Ripple, dB	FBW: $(f_{high} - f_{Low})/f_o$	Ratio: f_{high}/f_{low}
Max Flat	1.06667	3.13793
0.10	1.52340	7.37300
0.20	1.61330	9.34500
0.30	1.65300	10.4286
0.40	1.69270	12.0160
0.50	1.71565	13.1595
0.60	1.73860	14.3030

where:

FBW = Fractional Bandwidth = $(f_{high} - f_{Low})/f_o$

Ration = f_{high}/f_{low} = Bandwidth Ratio.

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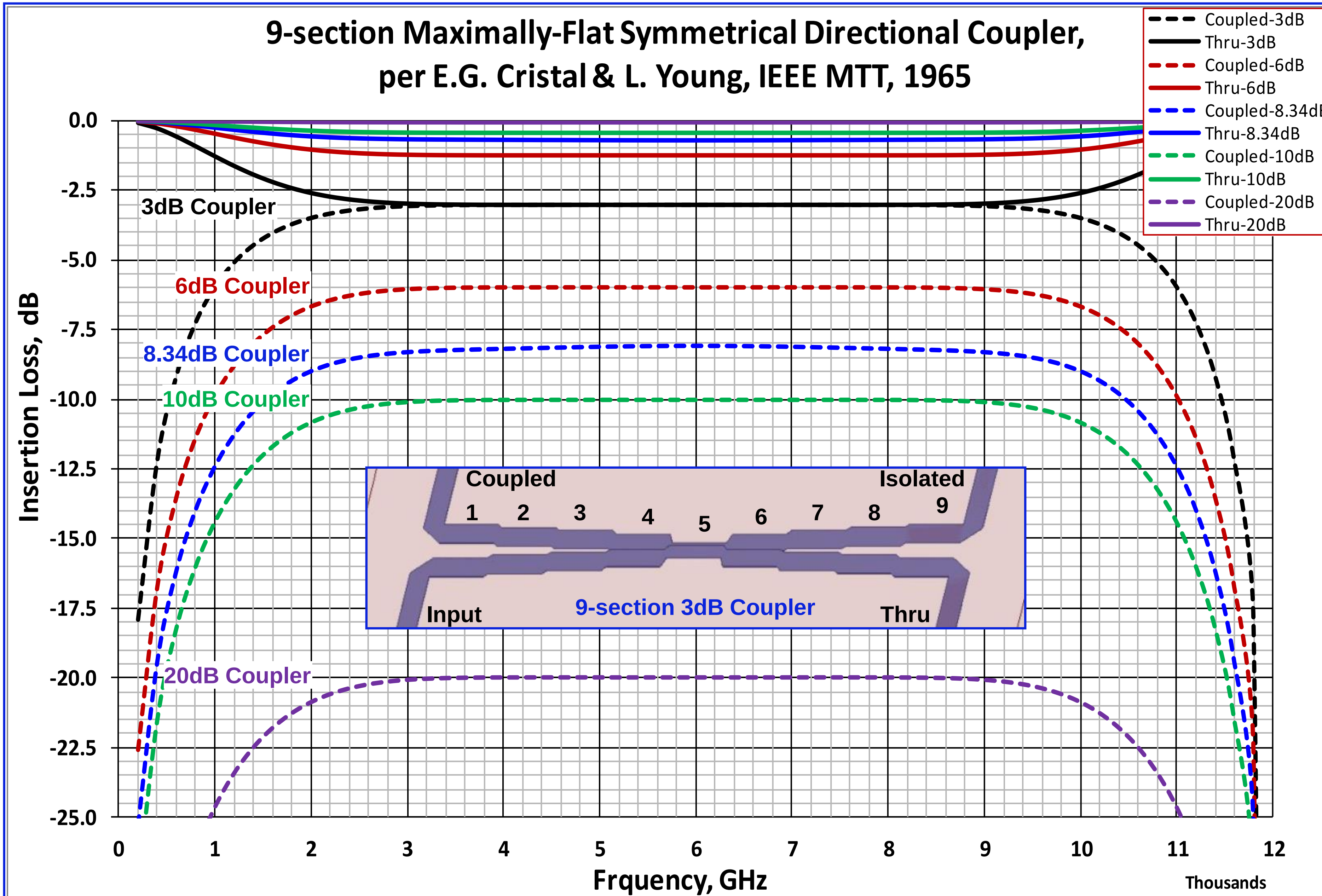
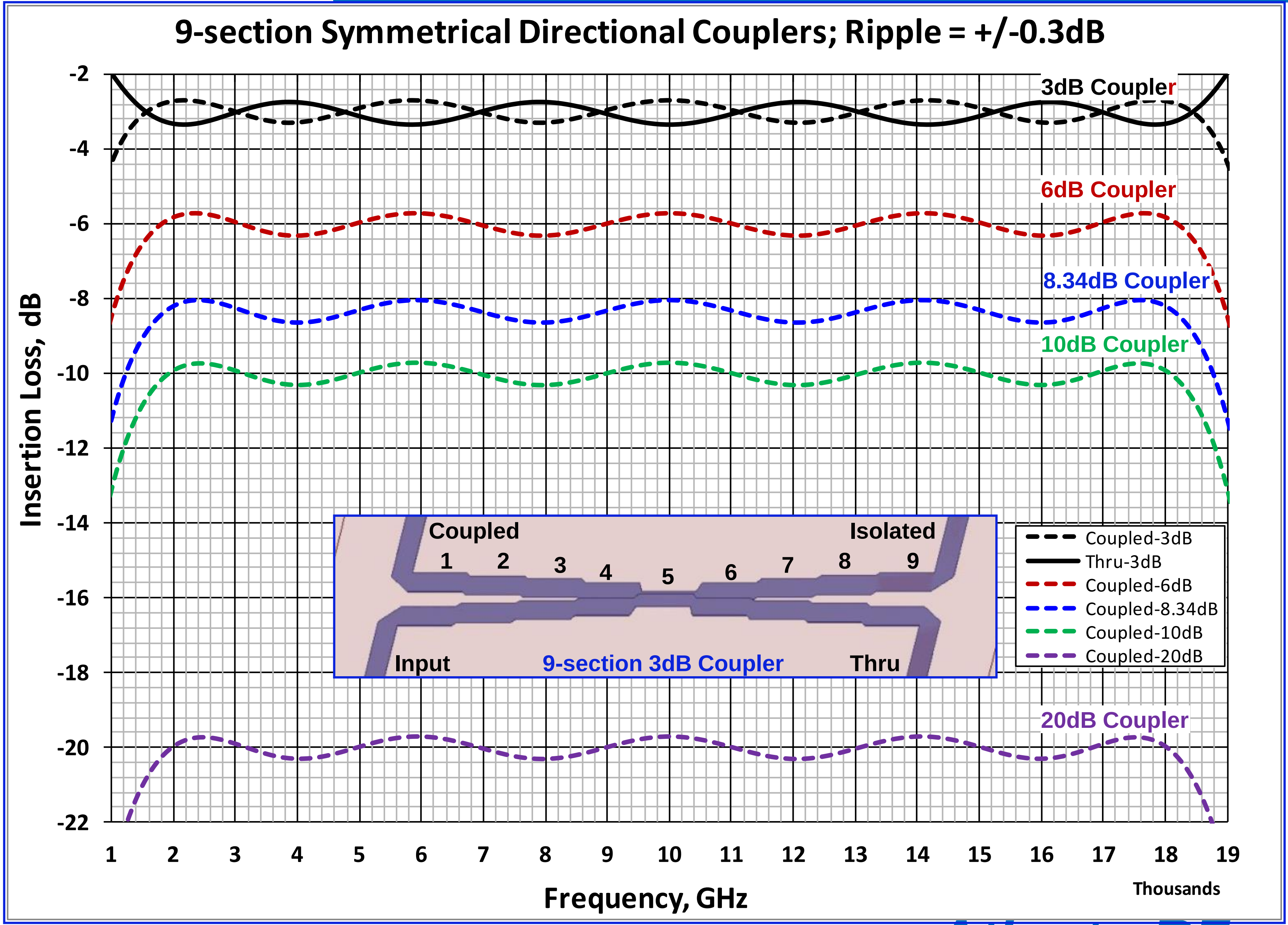


Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.



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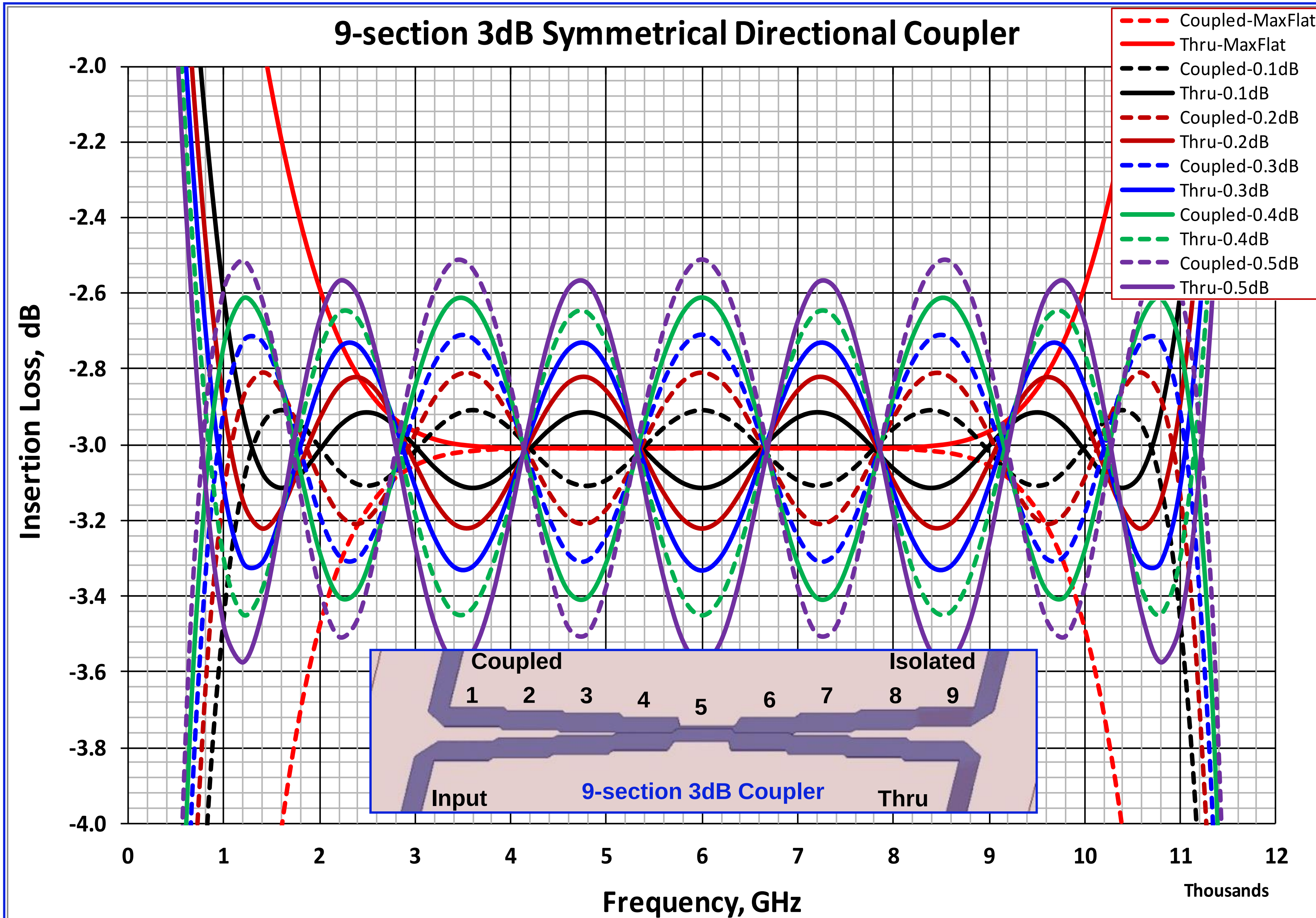


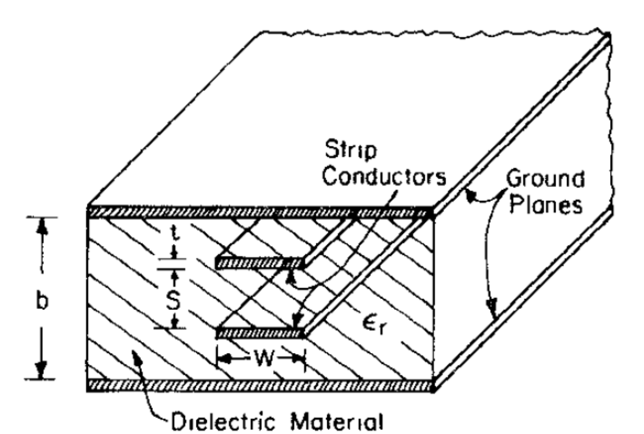
Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

Upper Operating Frequency of Stripline Couplers

Where higher-order non-TEM modes may launch & propagate.

The choice of ground plane separation: b, is dictated by the presence of higher-order modes in the stripline's triplate construction. Vendelin has proposed that the maximum usable frequency for a particular ground plane separation: b, in stripline construction is given by:

$$F_{\max} = \frac{30}{\sqrt{\varepsilon_r}\left(2W + \frac{\pi b}{2}\right)}(GHz)$$



where: W is the center conductor's width, cm.
b is the substrate's total thickness, cm.

Atlanta RF's CAE software product: TEMcoupler, reports the coupler's maximum usable frequency point where higher-order modes *may* propagate, based on your coupler's ground plane spacing and the synthesized strip width.

Vendelin G. D., "Limitations on stripline Q", *Microwave Journal*, 1970,13, pp. 63-69.

Insertion Loss in Directional Couplers

Coupled Loss, Resistive Loss & Reflected Loss

Insertion Loss measured through any directional coupler is the sum of various loss mechanisms, such as:

1. Coupled loss: RF energy entering the coupled RF path in the coupler, thereby decreasing the RF signal exiting the coupler's main thru path.
   a. Includes RF energy 'lost' due to poor isolation.
2. Resistive loss: RF energy dissipated inside the coupler due to energy absorption in the center conductor strips' metal, absorption in the top & bottom outer conductors' metal (ground plane), and absorption in the dielectric material supporting the center strips (= loss tangent).
   a. Resistive loss is dependent on materials selected to construct the coupler, including the surface roughness on metal surfaces.
3. Reflected loss: RF energy reflected at the RF port(s), which does not pass thru the coupler and, thereby, is not detected at the coupler's output port.
   a. Reflected loss can be caused by poor impedance interface at the RF connectors, poor impedance in the coupled sections, and various discontinuities inside the coupled section, like: strip's transitions.

Additional insertion loss can occur if the RF signal enters the coupler & converts to higher-order propagation modes: non-TEM mode.

Insertion Loss in Directional Couplers

Coupled Loss, Resistive Loss & Reflected Loss

1. Main line (thru-path) insertion loss caused by coupling value:

Coupling Ratio	Coupled Path Output (dB)	Coupled Path Power Ratio	Main Line Power Ratio	Main Line Loss
3 dB	-3 dB	$0.50\ P_{IN}$	$0.50\ P_{IN}$	3.0 dB
6 dB	-6 dB	$0.25\ P_{IN}$	$0.75\ P_{IN}$	1.25 dB
10 dB	-10 dB	$0.10\ P_{IN}$	$0.90\ P_{IN}$	0.46 dB
20 dB	-20 dB	$0.01\ P_{IN}$	$0.99\ P_{IN}$	0.04 dB
30 dB	-30 dB	$0.001\ P_{IN}$	$0.999\ P_{IN}$	0.004 dB

2. Main line (thru-path) insertion loss caused by reflected RF power/loss:

VSWR	Return Loss (dB)	Trans. Loss (dB)	VSWR	Return Loss (dB)	Trans. Loss (dB)
1.00	99.9	0.000	1.40	15.8	0.122
1.05	32.3	0.003	1.50	14.0	0.177
1.10	26.4	0.010	1.60	12.7	0.238
1.15	23.1	0.021	1.70	11.7	0.302
1.20	20.8	0.036	1.80	10.9	0.370
1.25	19.1	0.054	1.90	10.2	0.440
1.30	17.7	0.075	2.00	9.5	0.512

Dielectric Materials: RF/Microwave Application

Commercially-available high-frequency dielectric materials

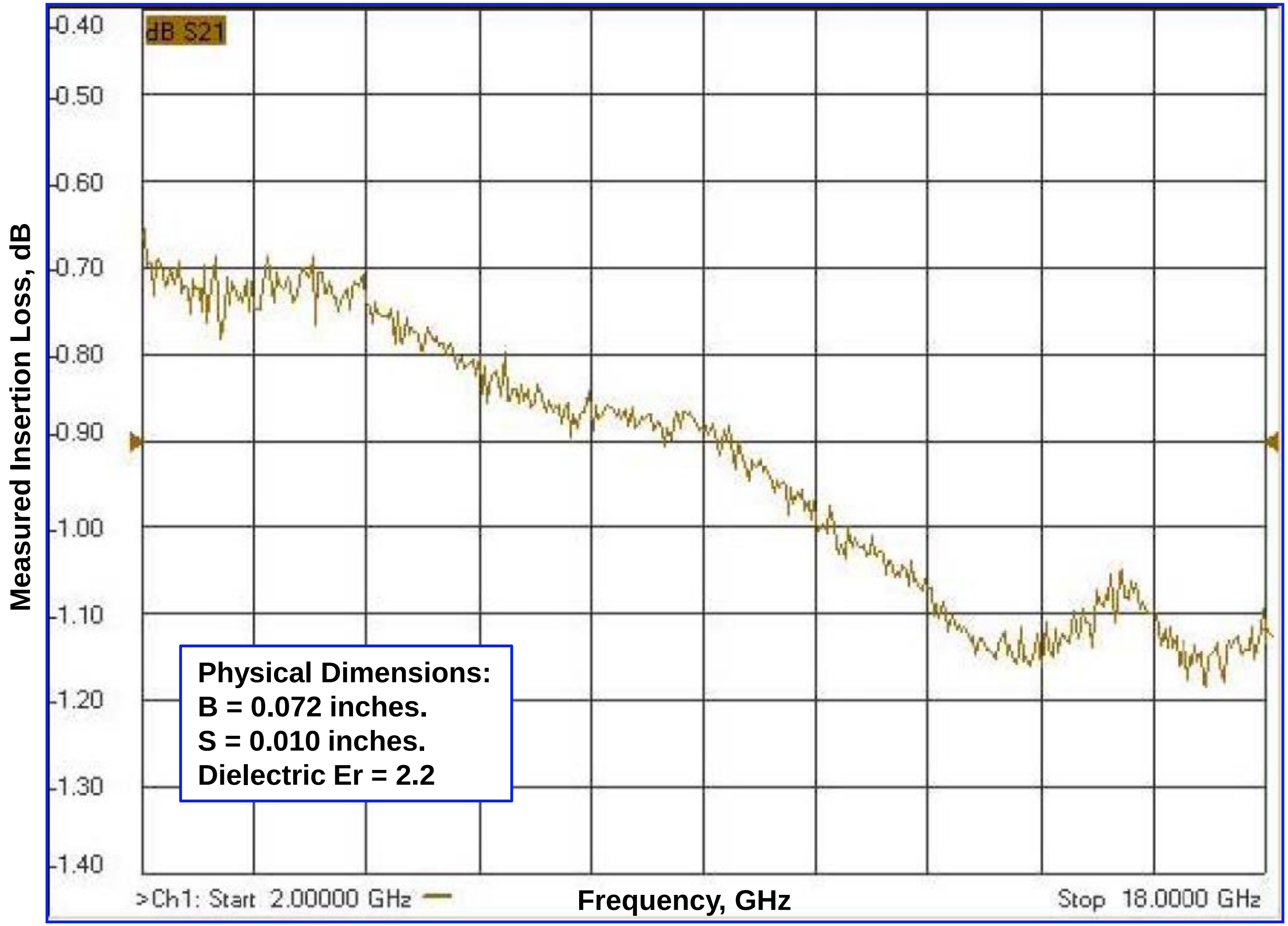
Commercially-available dielectric substrate materials are manufactured by:

- Arlon Electronic Materials: www.arlon-med.com
- Isola Group: www.isola-usa.com
- Nelco: http://www.parkelectro.com/parkelectro/neltec_rf_about.asp
- Polyflon Company: www.polyflon.com
- Rogers Corporation: www.rogerscorp.com
- Sheldahl: www.sheldahl.com
- Taconic Advanced Dielectric Division: www.taconic-add.com

Note: N-section symmetrical directional couplers constructed using layers of dielectric materials to realize offset and/or broadside coupled strip transmission lines often use dielectric materials whose dielectric constant < 3.0 (often: $E_r = 2.2$).

Example: Measured Loss thru a 10dB Coupler

9-section Symmetrical 10dB Symmetrical Directional Coupler



Yi Ge & Gaofeng Guo: 'The Design of Broadband Stripline Directional Coupler', 2012 5th Global Symposium on Millimeter Waves (GSMM 2012), pp 307 thru 311.

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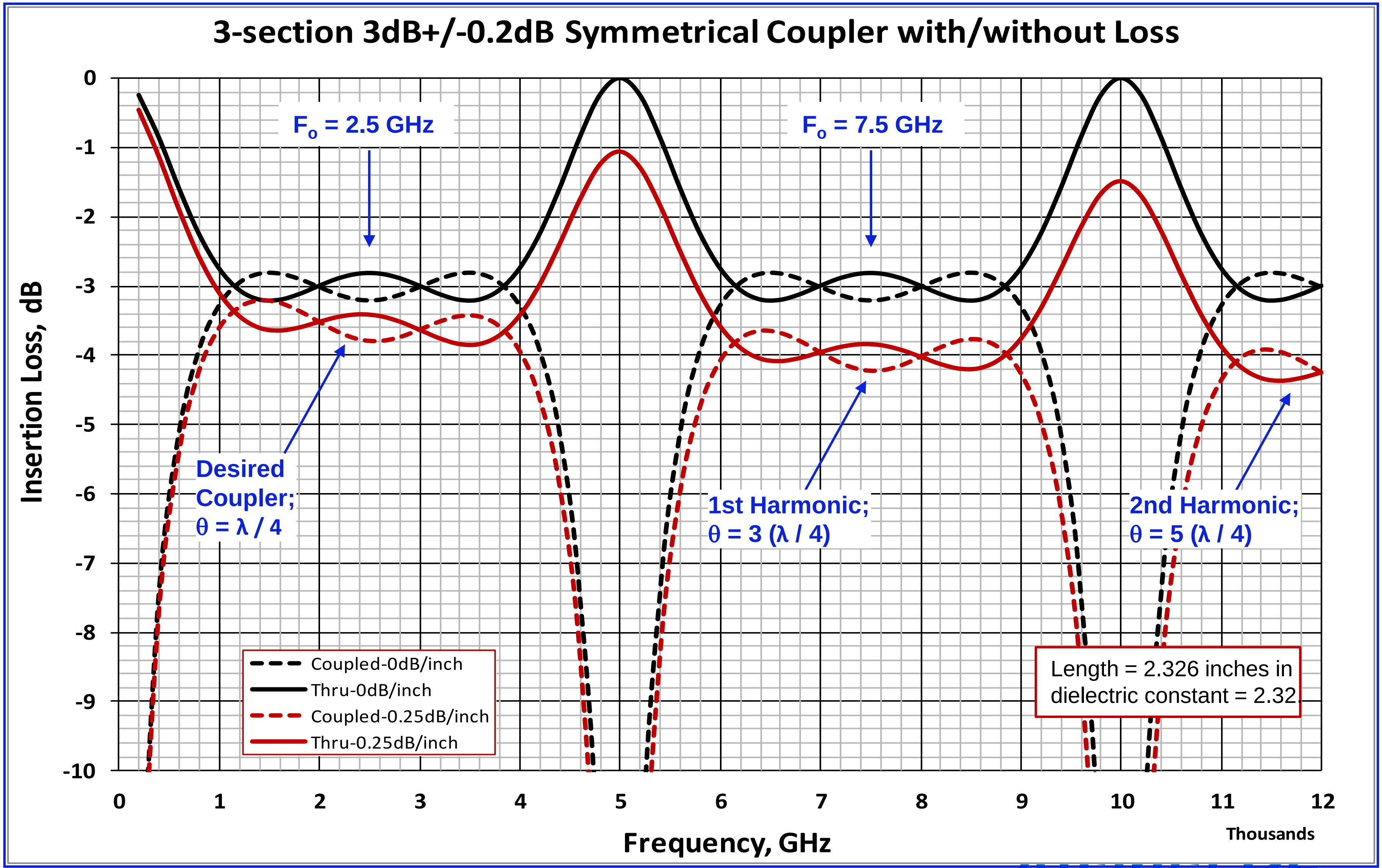
Insertion Loss Profile of a 3dB Symmetrical Coupler

Insertion Loss = 0.25 dB/inch at F_o = 2.5 GHz



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

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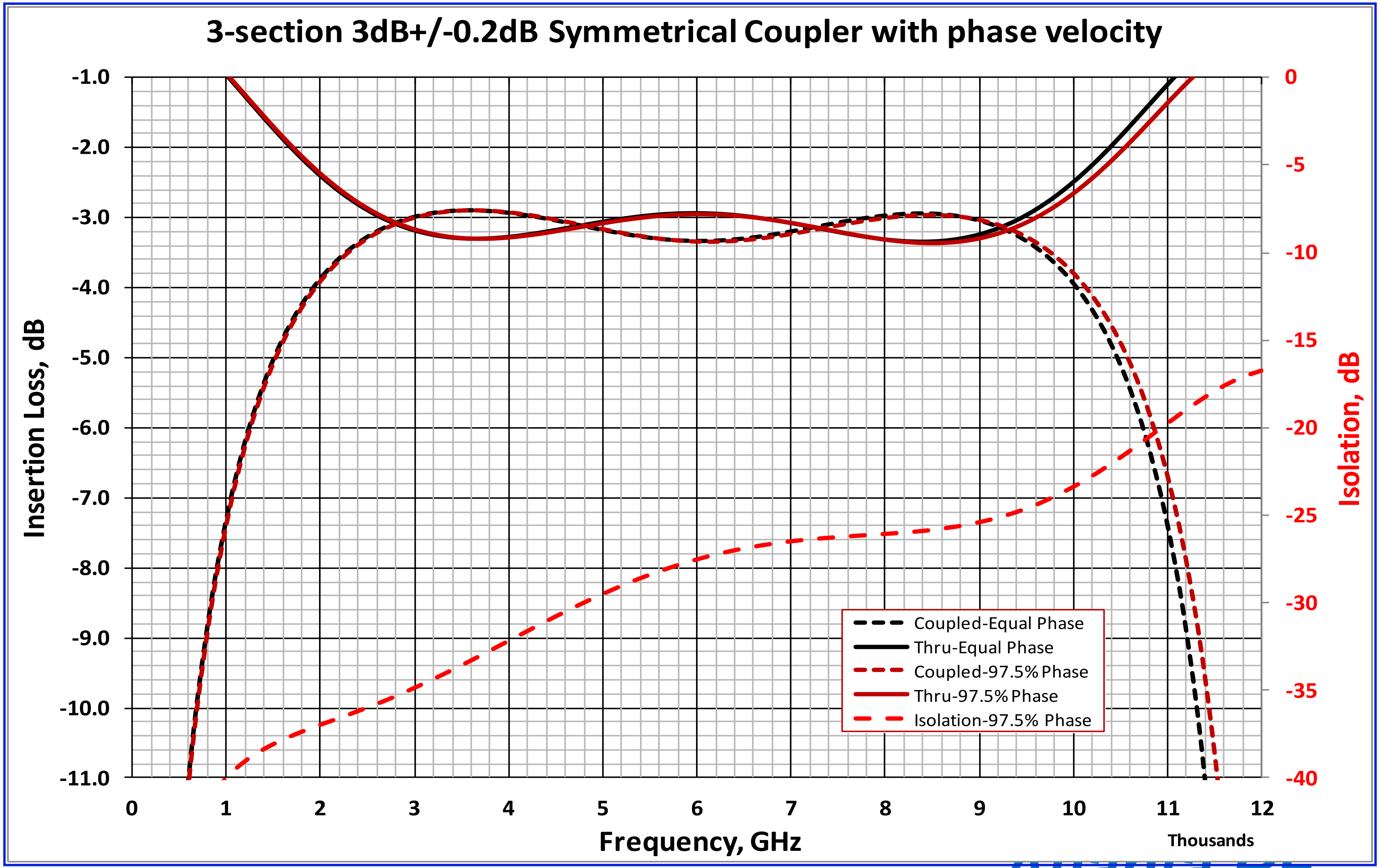
Isolation degradation caused by different Phase Velocity

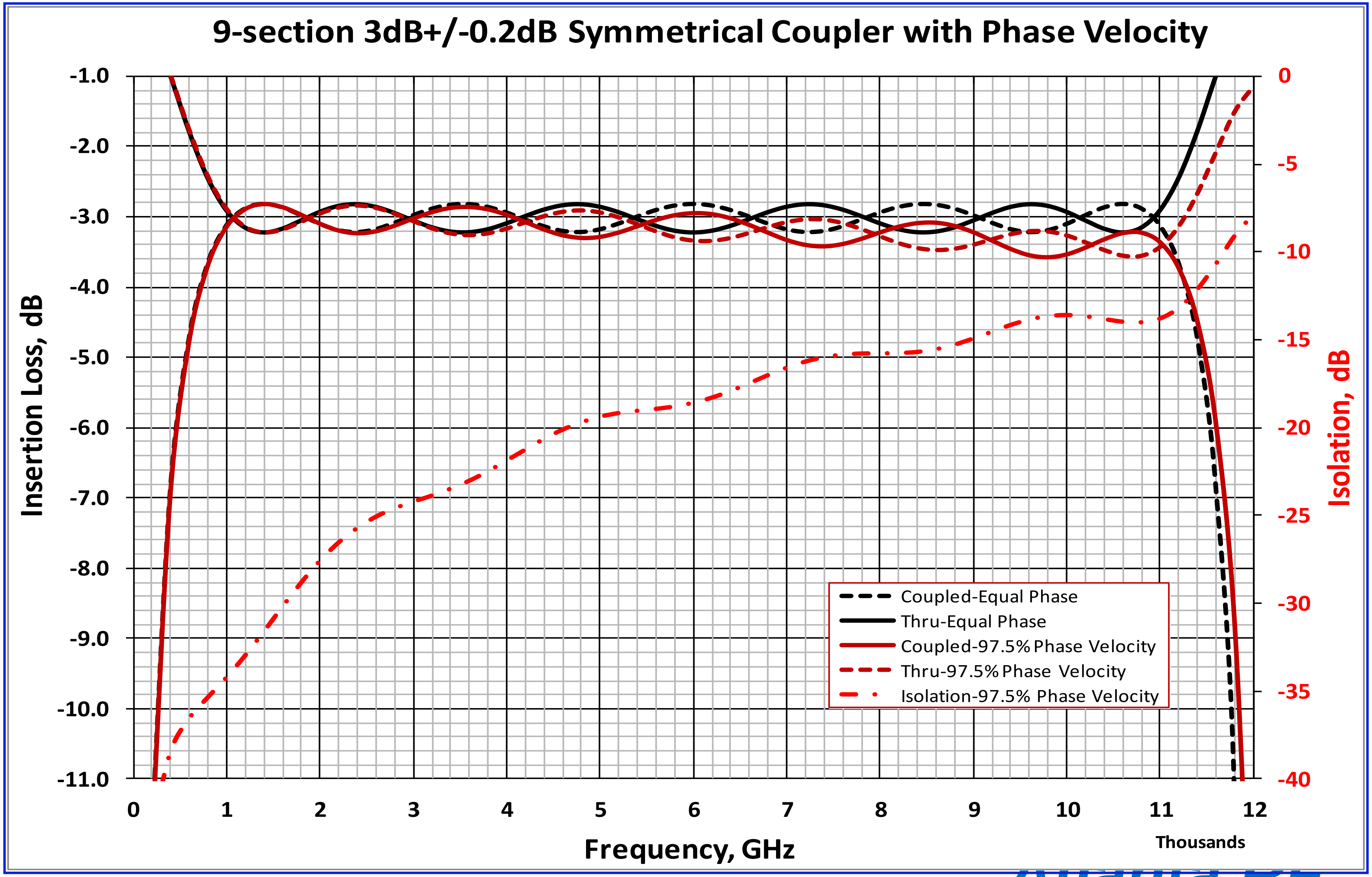
Even-Mode Phase Velocity = 97.5% of Odd-Mode Phase Velocity



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

Isolation degradation caused by different Phase Velocity

Even-Mode Phase Velocity = 97.5% of Odd-Mode Phase Velocity



Note: Electrical synthesis & frequency analysis using CAE software product: TEMcoupler.

Examples: N-section Symmetrical Couplers

Test Cases: 3dB, 6dB and 10dB symmetrical directional couplers

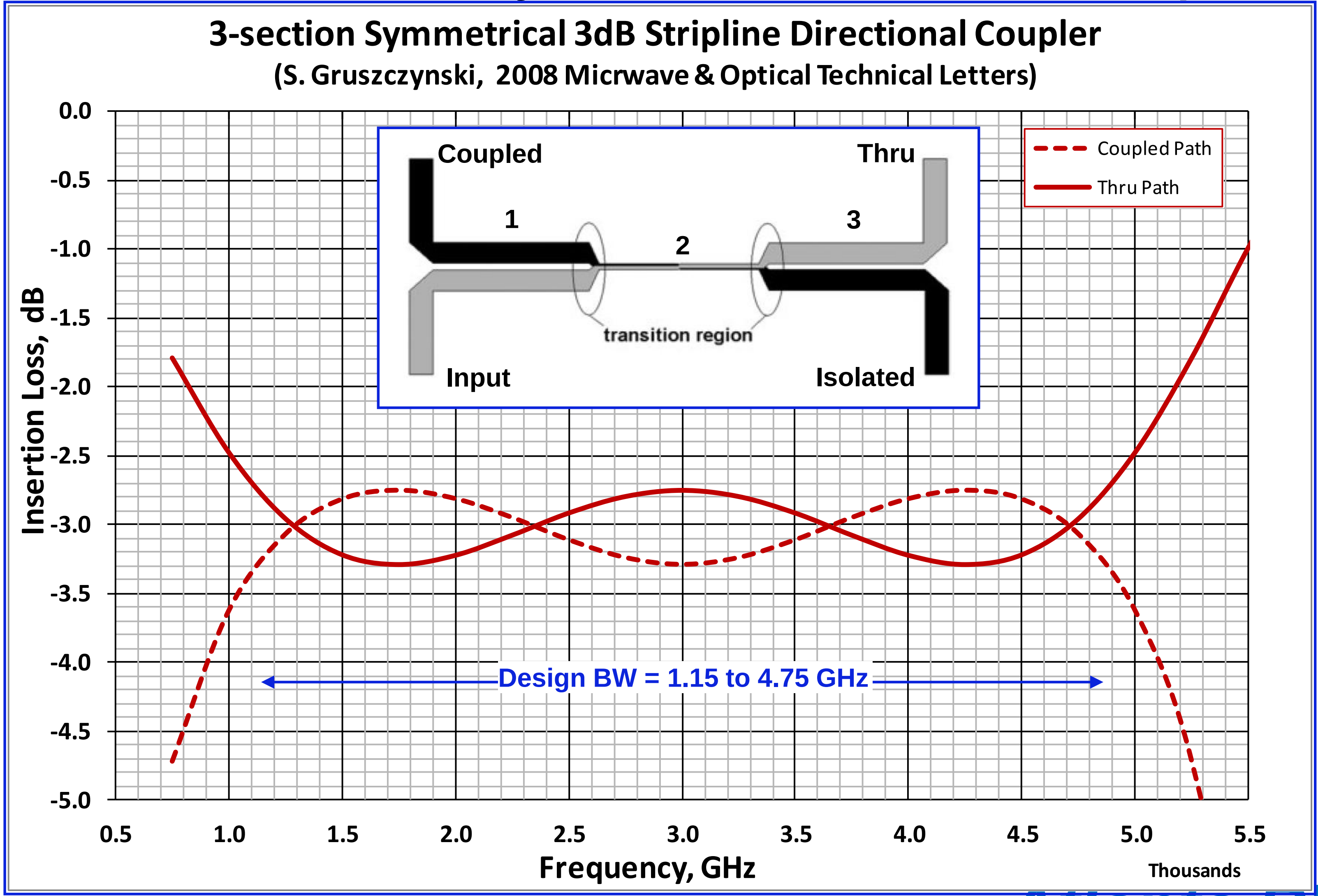
The following three (3) examples provide the predicted RF performance of N-section Symmetrical Directional Couplers published in technical articles when synthesized & analyzed by Atlanta RF's CAE software product: TEMcoupler:

1. S. Gruszczynski & K. Wincza: 'Design OF High-Performance Broadband Multisection Symmetrical 3dB Directional Couplers', Microwave and Optical Technology Letter, Vol. 50, No. 3, March 2008 (3-secton 3dB Coupler).
2. R. Piña Piña, A. Dueñas Jiménez & C. A. Bonilla Barragán: 'The Circuit and Network Analysis of Some Signal Separation Structures Constituting Microwave Six-Port Reflectometers', Universal Journal of Electrical and Electronic Engineering 2(4): 183-196, 2014 (3-section 6dB Coupler).
3. Yi Ge & Gaofeng Guo: 'The Design of Broadband Stripline Directional Coupler', 2012 5th Global Symposium on Millimeter Waves (GSMM 2012), pp 307 thru 311 (9-section 10dB Coupler).

Observation: All synthesis & analysis results from Atlanta RF's CAE software product: TEMcoupler, show excellent agreement with published electrical response & physical dimensions.

Example: 3-section Symmetrical 3dB Coupler

S. Gruszczynski & K. Wincza: 'Design of High Performance Broadband Multisection Symmetrical 3dB Directional Couplers'



Note: Insertion Loss = 0.0dB/inch in CAE software product: TEMcoupler.

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TEMcoupler (v. 1.3) Date: 5/15/2015 at 22:41:22Hours

RF/Microwave Computer-Aided Engineering Design Data For
Offset Broadside-Coupled Strip Transmission Lines:

Synthesis of dimensional parameters for your 3-section Stripline Directional Coupler with offset broadside-coupled strip transmission lines (zero strip thickness) results in the following design data:

Flow = 0.00 MHz	B = 0.1220 Inches	Coupling = 0.000 dB
Fo = 3000.00 MHz	S = 0.0020 Inches	Ripple = 0.000 dB
Fhigh= 0.00 MHz	Er = 3.38	Zo = 50.000 Ohms

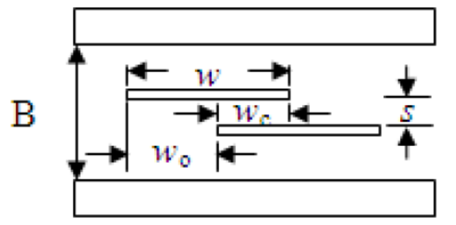
Coupled	Impedances			Phase Velocity		Loss,dB/Inch		
Section	Zoe	Zoo	Coupling	Even	Odd	Even	Odd	Length
I	Ohms	Ohms	dB	Mode	Mode	Mode	Mode	Inches
-------	-------	------	--------	------	------	------	------	------
1	61.5	40.65	13.803	1	1	0	0	0.5354
2	174.9	14.294	1.423	1	1	0	0	0.5354
3	61.5	40.65	13.803	1	1	0	0	0.5354

In a dielectric with Er = 3.38, Total Length of Coupler = 1.6061

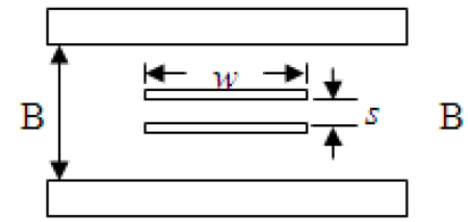
	Strip Dimensions in Inches				Strip Dimensions: Millimeters			
Coupled	Tight Coupling		Loose Coupling		Tight Coupling		Loose Coupling	
Section	Strip	Strip	Strip	Strip	Strip	Strip	Strip	Strip
I	Width	Offset	Width	Offset	Width	Offset	Width	Offset
-------	------	------	------	------	------	------	------	------
1	0.0728	0.0767	0.0658	0.0865	1.8487	1.9477	1.6702	2.1963
2	0.0125	0.0035	0.0125	0.005	0.3176	0.088	0.3176	0.1258
3	0.0728	0.0767	0.0658	0.0865	1.8487	1.9477	1.6702	2.1963

For Zo = 50.0 Ohms, strip width = .0712 inches (1.8091 mm).
Maximum usable operating frequency = 36058.5 MHz before possible launch of higher-order modes.

Physical dimensions synthesized by Atlanta RF's CAE RF software product: *TEMcoupler*, for 3-section 3dB Symmetrical Coupler based on design presented by Gruszczynski (2008).



"Offset"



"Broadside"

where:

- B = Ground plane spacing.
- S = Spacing between strips.
- W = Strip width.
- Wo = Strip offset.

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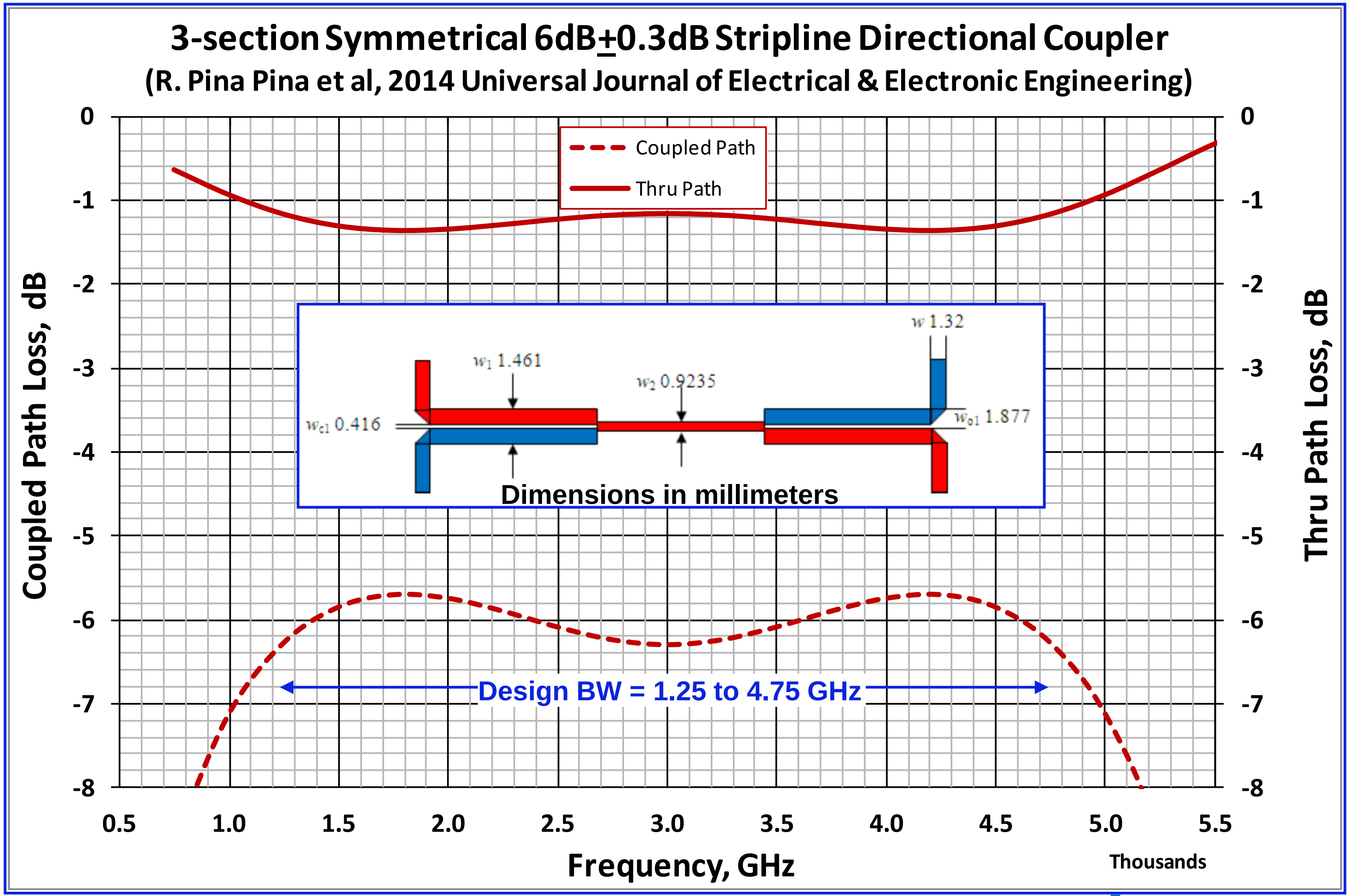
Example: 3-section Symmetrical 6dB Coupler

R. Pina Pina et al: 'The Circuit & Network Analysis of Some Signal Separation Structures Constituting uWave 6-port Reflectometers'



Note: Insertion Loss = 0.0dB/inch in CAE software product: TEMcoupler.

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TEMcoupler (v. 1.3) Date: 5/15/2015 at 21: 5:16Hours

RF/Microwave Computer-Aided Engineering Design Data For

Offset Broadside-Coupled Strip Transmission Lines:

Synthesis of dimensional parameters for your 3-section Stripline Directional Coupler with offset broadside-coupled strip transmission lines (zero strip thickness) results in the following design data:

Flow = 1250.00 MHz	B = 0.0733 Inches	Coupling = 6.02dB
Fo = 3000.00 MHz	S = 0.01 Inches	Ripple = 0.3dB
Fhigh= 4750.00 MHz	Er = 2.2	Zo = 50.0 Ohms

Coupled	Impedances			Phase Velocity		Loss,dB/Inch		
Section I	Zoe Ohms	Zoo Ohms	Coupling dB	Even Mode	Odd Mode	Even Mode	Odd Mode	Length Inches
-------	-------	------	--------	------	------	------	------	------
1	56.813	44.004	17.921	1.000	1.000	0.000	0.000	0.6636
2	109.5	22.831	3.676	1.000	1.000	0.000	0.000	0.6636
3	56.813	44.004	17.921	1.000	1.000	0.000	0.000	0.6636

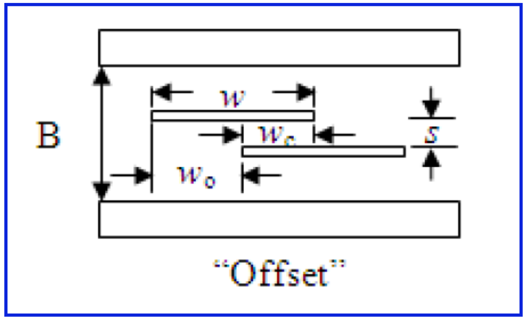
In a dielectric with Er = 2.20, Total Length of Coupler = 1.9907

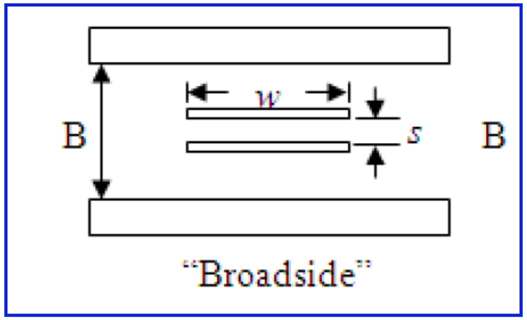
	Strip Dimensions in Inches				Strip Dimensions: Millimeters			
Coupled	Tight Coupling		Loose Coupling		Tight Coupling		Loose Coupling	
Section I	Strip Width	Strip Offset	Strip Width	Strip Offset	Strip Width	Strip Offset	Strip Width	Strip Offset
---------	---------	---------	---------	---------	---------	---------	---------	---------
1	0.0600	0.0681	0.0575	0.0739	1.5248	1.7298	1.4609	1.8768
2	0.0364	0.0000	0.0375	0.0081	0.9233	0.0000	0.9529	0.2051
3	0.0600	0.0681	0.0575	0.0739	1.5248	1.7298	1.4609	1.8768

For Zo = 50.0 Ohms, strip width = .0595 inches (1.5122 mm).

Maximum usable operating frequency = 19519.1 MHz before possible launch of higher-order modes.

Physical dimensions synthesized by Atlanta RF's CAE RF software product: *TEMcoupler*, for 3-section 6dB Symmetrical Coupler based on design presented by R. Pina Pina (2014).





where:

- B = Ground plane spacing.
- S = Spacing between strips.
- W = Strip width.
- Wo = Strip offset.

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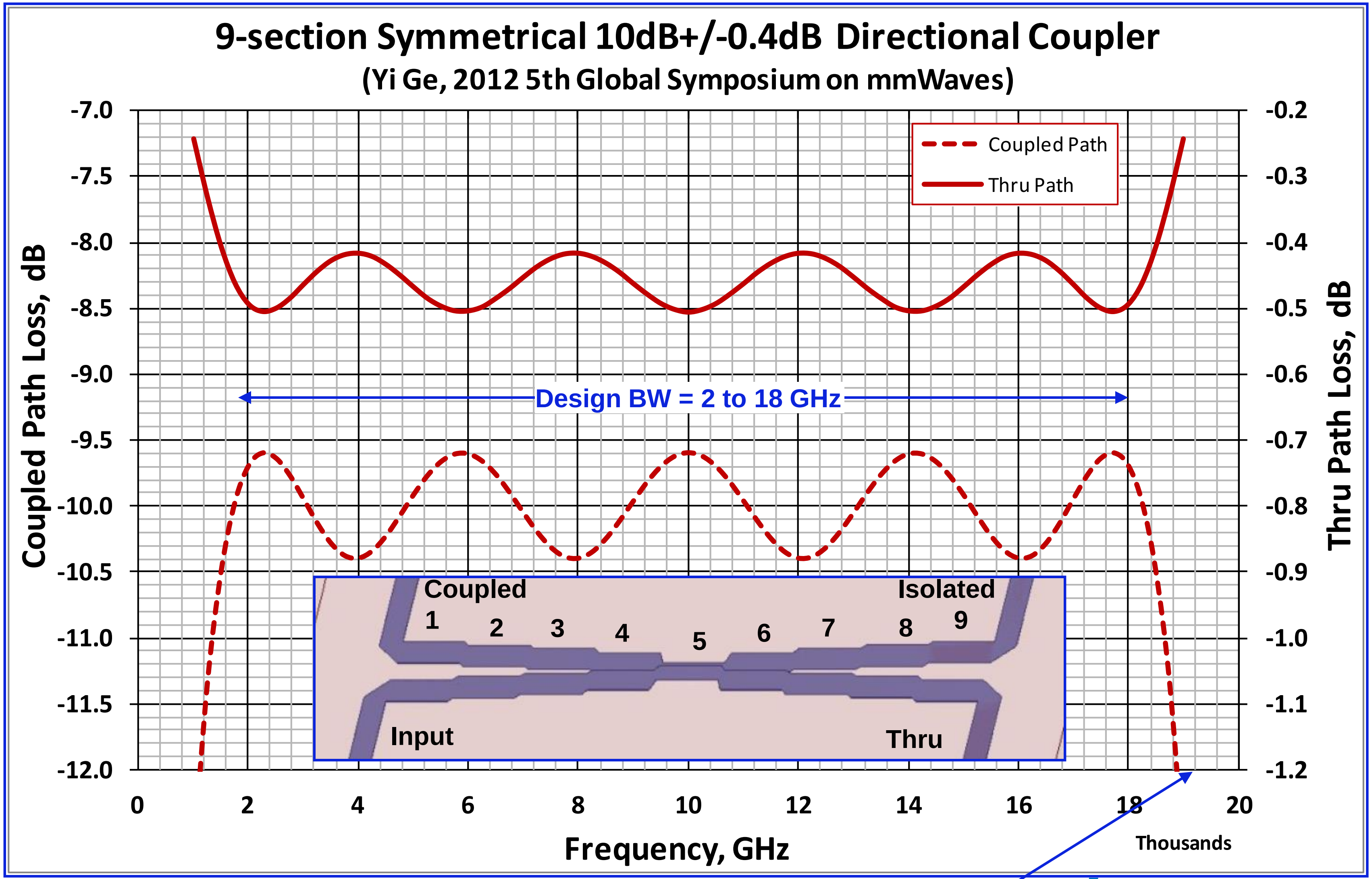
Example: 9-section Symmetrical 10dB Coupler

Yi Ge & Gaofeng Guo: 'The Design of Broadband Stripline Coupler'



Predicted F_{MAX} = 19.37 GHz

Note: Insertion Loss = 0.0dB/inch in CAE software product: TEMcoupler.

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TEMcoupler (v. 1.3) Date: 5/16/2015 at 20:26:25Hours

RF/Microwave Computer-Aided Engineering Design Data For

Offset Broadside-Coupled Strip Transmission Lines:

Synthesis of dimensional parameters for your 9-section Stripline Directional Coupler with offset broadside-coupled strip transmission lines (zero strip thickness) results in the following design data:

Flow = 1800.00 MHz	B = 0.0720 Inches	Coupling = 10.000 dB
Fo = 10000.00 MHz	S = 0.0100 Inches	Ripple = 0.400 dB
Fhigh= 18200.00 MHz	Er = 2.2000	Zo = 50.000 Ohms

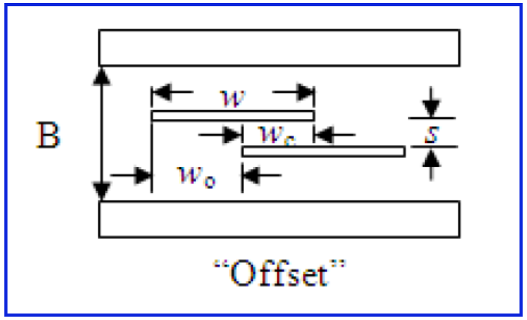
Coupled	Impedances			Phase Velocity		Loss,dB/Inch		
Section	Zoe	Zoo	Coupling	Even	Odd	Even	Odd	Length
I	Ohms	Ohms	dB	Mode	Mode	Mode	Mode	Inches
-------	-------	------	--------	------	------	------	------	------
1	51.521	48.524	30.473	1.000	1.000	0.000	0.000	0.1991
2	53.502	46.727	23.402	1.000	1.000	0.000	0.000	0.1991
3	57.156	43.74	17.524	1.000	1.000	0.000	0.000	0.1991
4	64.889	38.528	11.873	1.000	1.000	0.000	0.000	0.1991
5	98.037	25.501	4.625	1.000	1.000	0.000	0.000	0.1991
6	64.889	38.528	11.873	1.000	1.000	0.000	0.000	0.1991
7	57.156	43.74	17.524	1.000	1.000	0.000	0.000	0.1991
8	53.502	46.727	23.402	1.000	1.000	0.000	0.000	0.1991
9	51.521	48.524	30.473	1.000	1.000	0.000	0.000	0.1991

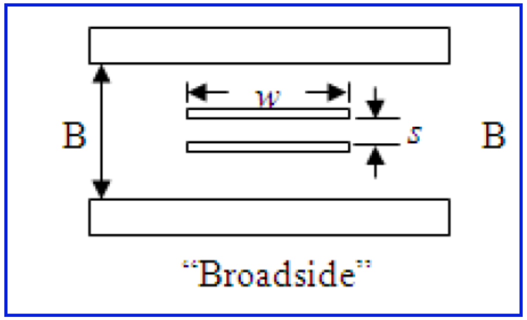
In a dielectric with Er = 2.20, Total Length of Coupler = 1.7917

	Strip Dimensions in Inches				Strip Dimensions: Millimeters			
Coupled	Tight Coupling		Loose Coupling		Tight Coupling		Loose Coupling	
Section	Strip	Strip	Strip	Strip	Strip	Strip	Strip	Strip
I	Width	Offset	Width	Offset	Width	Offset	Width	Offset
-------	------	------	------	------	------	------	------	------
1	0.0648	0.0778	0.0583	0.1065	1.6466	1.9759	1.4806	2.7052
2	0.0624	0.0735	0.0578	0.0876	1.5857	1.8660	1.4687	2.2245
3	0.0585	0.0662	0.0563	0.0713	1.4865	1.6806	1.4288	1.8119
4	0.0520	0.0530	0.0516	0.0539	1.3208	1.3462	1.3104	1.3679
5	0.0387	0.0139	0.0387	0.0164	0.9837	0.3542	0.9837	0.4154
6	0.0520	0.0530	0.0516	0.0539	1.3208	1.3462	1.3104	1.3679
7	0.0585	0.0662	0.0563	0.0713	1.4865	1.6806	1.4288	1.8119
8	0.0624	0.0735	0.0578	0.0876	1.5857	1.8660	1.4687	2.2245
9	0.0648	0.0778	0.0583	0.1065	1.6466	1.9759	1.4806	2.7052

For Zo = 50.0 Ohms, strip width = .0584 inches (1.4835 mm).
Maximum usable operating frequency = 19370.8 MHz before possible launch of higher-order modes.

Physical dimensions synthesized by Atlanta RF's CAE RF software product: *TEMcoupler*, for 9-section 10dB Symmetrical Coupler based On design presented by Ge and Guo (2012).





where:

- B = Ground plane spacing.
- S = Spacing between strips.
- W = Strip width.
- Wo = Strip offset.

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Ripple Bandwidth Comparison: 3dB Couplers

Compare Asymmetrical to Symmetrical N-section 3dB Couplers

Asymmetrical Couplers			Symmetrical Couplers			BW Ratio of
# Sections	Ripple	B	# Sections	Ripple	B	Asym/Sym
3-section	0.0 dB	3.00000	3-section	0 dB	2.15790	1.390
5-section	0.0 dB	4.85366	5-section	0 dB	3.44444	1.409
3-section	0.1 dB	4.25676	3-section	0.1 dB	3.03063	1.405
5-section	0.1 dB	7.40000	5-section	0.1 dB	4.93114	1.501
3-section	0.2 dB	5.29967	3-section	0.2 dB	3.83085	1.383
5-section	0.2 dB	9.30000	5-section	0.2 dB	6.29714	1.477
3-section	0.3 dB	6.23780	3-section	0.3 dB	4.52271	1.379
5-section	0.3 dB	10.90000	5-section	0.3 dB	7.46462	1.460
3-section	0.4 dB	7.01003	3-section	0.4 dB	5.17521	1.355
5-section	0.4 dB	12.36364	5-section	0.4 dB	8.55845	1.445
3-section	0.5 dB	7.80125	3-section	0.5 dB	5.81489	1.342
5-section	0.5 dB	13.63636	5-section	0.5 dB	9.62609	1.417
3-section	0.6 dB	8.58855	3-section	0.6 dB	6.45616	1.330
5-section	0.6 dB	15.00000	5-section	0.6 dB	10.69292	1.403
3-section	0.7 dB	9.43425	3-section	0.7 dB	7.10860	1.327
5-section	0.7 dB	16.40000	5-section	0.7 dB	11.77568	1.393

Observation:

Asymmetrical N-section 3dB Couplers produce an increase in operating bandwidth that is 33% to 50% wider than Symmetrical N-section 3dB Couplers.

Recall:

- Asymmetrical Couplers can have N = 2, 3, 4, 5, 6, etc sections.
- Symmetrical Couplers can have N = 3, 5, 7, 9, etc sections.
- Comparison: N = 3, 5, 7, 9, etc.
- Ripple Bandwidth = F_{HIGH}/F_{LOW}.
- Ripple = +/- x.xdB across operating frequency range.
- Asymmetrical Couplers do not maintain 90º phase offset in the coupled path.

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Summary: N-section Symmetrical Couplers

1. The electrical synthesis of N-section symmetrical directional couplers up to N= 9 sections are readily performed using Atlanta RF's CAE software product: TEMcoupler.
2. Once synthesized, TEMcoupler produces a frequency analysis of your N-section symmetrical coupler, which includes the scattering parameters at each RF port.
3. The physical dimensions of your coupler are synthesized to realize broadside coupled strips: with or without strip offset, using layered dielectric stripline construction.
4. The frequency response options for your N-section symmetrical coupler includes:
    a. Insertion Loss, dB/inch.
    b. Phase velocity differences between the even-mode & odd-mode, which can simulate the RF response of quasi-TEM Mode couplers, like: Construction in microstrip.

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Atlanta RF LLC was founded to provide engineering solutions, design software solutions, and product development solutions to the high-frequency RF/microwave industry in the areas of: Telecommunications (ground segment), Satellite (space segment) and military/defense (RF front-ends).

Through teamwork, Atlanta RF applies our diverse technical experience to your project's challenges with creative and innovative solutions while holding ourselves accountable fo the results. With professionalism and commitment to our clients, Atlanta RF will be there for you, both today and tomorrow.

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Or, contact Atlanta RF by phone at: 678-445-5544, to reach our Atlanta-area office in Georgia, USA, and discuss our support to your current or future projects & products.

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