## **Coupled-Ladder Reflectionless Filters** Latin America Microwave Conference, San Jose 12/2023

#### Matt Morgan, NRAO

# **Reflectionless Filters**



#### What is a Reflectionless Filter?







#### **Issues with Conventional Filters**





#### **Benefits of Reflectionless Filters**





#### **Once Called** *Constant-Resistance Networks*

#### Otto Zobel, 1928



ically applied to the case of a 104-mil open-wire smooth line having the constants per loop mile (for wet weather, and assumed independent of frequency),

> L' = 3.66 mh.;R' = 10.12 ohms;G' = 3.20 micromhos; C' = .00837 mf.

The corresponding simulating network for a length *l* is shown structurally in Fig. 23, where

#### Hendrik Bode, 1945

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The element values of the first degree networks are given by explicit formulae in Fig. 12.2. The element values of the second degree networks are less easily written. For the structures of V and VI they can, however, be computed, and are shown, for the Zx branch, by Figs. 12.4 and 12.5. In the Brune networks represented by structures VII and VIII reasonably explicit formulae are hardly possible. It is simplest to give formulae for the lattice branch impedance as a whole, leaving the individual elements to be

	Structure	Requirements for Physical Realizability	Typical Attenuation and Phase Characteristics
•	- The second second	$ \begin{array}{l}  \mathbf{s}_1\mathbf{s}_2  \geq  \mathbf{b}_1\mathbf{b}_2  \\  \mathbf{b}_1\mathbf{s}_2^R \leq \mathbf{s}_1^R\mathbf{s}_2^R \\  \mathbf{b}_1\mathbf{s}_2^R \leq \mathbf{s}_1^R\mathbf{s}_2^R \\ \text{The b's are ordinarily complex.} \end{array}                                   $	
T		$ \begin{array}{ }  a_{1}a_{2}  \leq  b_{1}b_{2}  \\ \hline \frac{1}{2} + \frac{1}{2} \leq \frac{1}{2} + \frac{1}{2} \\ \hline b_{1}  b_{2} \leq \frac{1}{2} \\ \hline \text{The b's are ordinarily complex.} \\ \hline \text{The b's are say be real} \\ \text{or complex.} \end{array} $	1
*11	( the second sec	n_n_g  ≥  b_bg  b_tb_g = b_tb_g b_tb_g = b_tb_g The size criticarily com- pler. The b's may be real or compler.	1
*111	Current Curren	$ \begin{vmatrix} \mathbf{a}_1 \mathbf{e}_1 \end{vmatrix} = \begin{vmatrix} \mathbf{b}_1 \mathbf{b}_1 \\ \frac{1}{2} \mathbf{e}_1 \mathbf{e}_1 \end{vmatrix} = \frac{1}{2} \mathbf{e}_1 \mathbf{e}$	55

determined subsequently from this expression. If we write the lattice branch Z<sub>z</sub> as

$$Z_x = R_0 \frac{A_1 + A_3 p + A_5 p^2}{A_2 + A_4 p + A_6 p^2},$$
 (12-2)

the coefficients  $A_1 \cdots A_6$  must satisfy the system of equations

$$A_{1} - A_{2} = b_{1}b_{2}(A_{5} - A_{6}),$$

$$A_{1} + A_{2} = a_{1}a_{2}(A_{5} + A_{6}),$$

$$A_{3} - A_{4} = -(b_{1} + b_{2})(A_{5} - A_{6}),$$

$$A_{3} + A_{4} = -(a_{1} + a_{2})(A_{5} + A_{6}),$$
(12-3)



#### Port 1













$$_{21} = \frac{1}{Z_0 + Z_1}$$

#### **Realizability Limitations Lead to Excess Flat Loss**





## **Higher-Order Synthesis Complex (High Element Count)**



Frequency,  $\omega$ 



## **Renewed Interest**

- Discovery of coupled-ladder topologies has generated renewed interest in reflectionless filters.
- Many researchers now exploring different ways of implementing reflectionless filters
  - **Transmission-Lines** •
  - **Coaxial Resonators**
  - Surface-Acoustic Wave  $\bullet$
  - Substrate-Integrated Waveguide  $\bullet$
- Many of these new approaches are based on empirical modeling.
- For this talk, I will focus on the fundamental coupled-ladder solution.



# **Coupled Ladder Topology**





#### A Symmetric Two-Port Network, "N"





### A Symmetric Two-Port Network, "N"

Identical half-circuits





#### **Even-Mode Excitation**





#### **Even-Mode Excitation**





#### **Odd-Mode Excitation**





#### **Odd-Mode Excitation**





## **Even and Odd-Mode** Analysis









#### Duality

$$\Gamma_{even} = -\Gamma_{odd}$$

$$\frac{Z_{even} - Z_0}{Z_{even} + Z_0} = \frac{Z_0 - Z_{odd}}{Z_0 + Z_{odd}}$$

$$\frac{Z_e - 1}{Z_e + 1} = \frac{1 - Z_0}{1 + Z_0}$$

$$\frac{Z_e - 1}{Z_e + 1} = \frac{y_0 - 1}{y_0 + 1}$$

$$Z_e = y_0$$

































































#### **A Third-Order Reflectionless Filter**



(Element values are normalized for frequency and impedance.)







#### **Higher-Order Responses Not So Great**

(Element values are normalized for frequency and impedance.)







#### **Higher-Order Responses Not So Great**

(Element values are normalized for frequency and impedance.)







#### **Subnetwork Expansion**





### **Subnetwork Expansion**




#### **Subnetwork Expansion**







#### **Subnetwork Expansion**





#### **A Seventh-Order Reflectionless Filter**



(Element values are normalized for frequency and impedance.)





#### **Element Value Generalization**



(Element values are normalized for frequency and impedance.)





# **Topological Generalization**



(Element values are normalized for frequency and impedance.)







## **Limiting Ripple Factor**



(Element values are normalized for frequency and impedance.)







Stop-Band Rejection (dB)



(Element values are normalized for frequency and impedance.)





(Element values are normalized for frequency and impedance.)



44



(Element values are normalized for frequency and impedance.)













47







A little redundant...



49

#### **No More Negative Elements!**







# **All-Pole Topologies**



### **Type-II to Type-I Transformation**







### **Type-II to Type-I Transformation**







### **Type-II to Type-I Transformation**









#### **Type-I Transmission Equivalent to Standard Ladder** (but Reflectionless)





$g_4$	$g_5$	$g_6$	$g_7$
2.000	1.802	1.247	0.445
1.500	1.464	1.179	0.535
1.569	1.569	1.274	0.621
1.634	1.757	1.396	0.807
1.622	1.940	1.437	1.008
1.576	2.089	1.424	1.173
1.520	2.229	1.392	1.323
1.498	2.280	1.377	1.377
1.461	2.366	1.350	1.465
1.727	1.939	1.477	0.839

## **Negative Elements Removed As-Needed**



Legendre



A



 $\overline{m}$ 





#### Butterworth

# **Implementation: Discrete SMT**





#### **Deep Rejection Chebyshev Type-II Filter (***N***=7)**









#### Chebyshev Type-II Even-Order Filter (*N*=6)



Frequency (MHz)

### **Butterworth Filter (N=7)**





**Elliptic Filter** 





A. Guilabert, M. Morgan, and T. Boyd, "Reflectionless filters for generalized elliptic transmission functions," *IEEE Transactions on Circuits and Systems I*, vol. 66, no. 12, pp. 4606-4618, December 2019.

# **Implementation:** Monolithic Die







#### **Most Compact Implementation**







#### **GaAs Integrated Passive Device (IPD) Fabrication**

#### 625 MHz Low-Pass Filter



1.6–3.6 GHz Band-Pass Filter







#### GaAs IPD High-Pass Filter (N=7)





#### **Now Marketed by Mini-Circuits**





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Reflectionless filters were developed to improve sensitivity in the world's most powerful receivers...



#### **Exclusively from Mini-Circuits**

Patented topology absorbs and terminates stopband signals





#### Imagine what they could do for your system.





#### **Thin-Film on Quartz**

#### 60 GHz Low-Pass Filter (*N*=5)



#### 60 GHz High-Pass Filter (*N*=7)





## **Size and Frequency of Various Implementations**





#### References

#### **Books and Book Chapters**

- M. Morgan, *Reflectionless Filters*, Norwood, MA: Artech House, January 2017.
- M. Morgan, "Řeflectionless filter topologies," *Wiley Encyclopedia of Electrical and Electronics Engineering*, pp. 1-13, August 2019.
- M. Morgan, "Planar reflectionless filters." In J. Hong, ed., *Advances in Planar Filters Design*, London: SciTech Publishing, 2019.

#### Academic Papers and Magazine Articles

- A. Guilabert, M. Morgan, and T. Boyd, "Reflectionless filters for generalized elliptic transmission functions," *IEEE Transactions on Circuits and Systems I*, vol. 66, no. 12, pp. 4606-4618, December 2019.
- R. Shrotriya and M. Morgan, "Filtering without reflections: flattening multiplier chain conversion efficiency & more," *Microwave Journal White Paper*, September 2019.
- M. Morgan, W. Groves, and T. Boyd, "Reflectionless filter topologies supporting arbitrary low-pass ladder prototypes," *IEEE Transactions on Circuits and Systems I*, vol. 66, no. 2, pp. 594-604, February 2019.
- pp. 594-604, February 2019.
  M. Morgan, "Think outside the band: design and miniaturization of absorptive filters," *IEEE Microwave Magazine*, vol. 19, no. 7, pp. 54-62, November 2018.
- M. Morgan, "A better way to filter -- part I," *NRAO Blog*, March 29, 2018.
- R. Setty, B. Kaplan, M. Morgan, and T. Boyd, "Combining MMIC reflectionless filters to create UWB bandpass filters," *Microwave Journal*, vol. 61, no. 3, pp. 60-72, March 2018.
- M. Morgan and T. Boyd, "Reflectionless filter structures," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 4, pp. 1263-1271, April 2015.
- M. Morgan and T. Boyd, "Theoretical and experimental study of a new class of reflectionless filter," *IEEE Trans. Microwave Theory Tech.*, vol. 59, no. 5, pp. 1214-1221, May 2011.

#### **Application Notes**

- "Advantages of cascading reflectionless filters," Mini-Circuits Application Note, AN75-008.
- "Pairing mixers with reflectionless filters to improve system performance," Mini-Circuits Application Note, AN75-007.

#### Patents

- M. Morgan, "Deep rejection reflectionless filters," U.S. Patent No. 10,530,321, January 7, 2020, Taiwan Patent No. 1699970B, July 21, 2021.
- M. Morgan, "Sub-network enhanced reflectionless filter topology," U.S. Patent No. 9,705,467, July 11, 2017, No. 10,230,348, March 12, 2019, Taiwan Patent No. I581494B, May 1, 2017, People's Republic of China Patent No. 107078708B, February 9, 2021.
- M. Morgan, "Optimal response reflectionless filter topologies," U.S. Patent No. 10,516,378, December 24, 2019.
- M. Morgan, "Optimal response reflectionless filters," U.S. *Patent No. 10,374,577*, August 6, 2019, *No. 10,263,592*, April 16, 2019. *Taiwan Patent No. 1653826B*, March 11, 2019.
- M. Morgan, "Transmission line reflectionless filters," U.S. Patent No. 9,923,540, March 20, 2018, No. 10,277,189, April 30, 2019, Japan Patent No. 6652970B2, January 28, 2020, 6964152B2, October 20, 2021.
- M. Morgan, "Reflectionless filters," U.S. Patent No. 8,392,495, March 5, 2013. People's Republic of China Patent No.102365784B, July 30, 2014.



Reflectionles

ing is "what we do." We do much more	field's own perso
than that, of course. But I think it is true that this is what most of our more com-	One might o certain point of
plex tasks ultimately boil down to. To design an ampli- fier, you have to match the impedance of the transistor.	ubiquitous buil designed to echi
To design an antenna, you have to match its radiation impedance. We do it by rote, without thinking, like a	in its stopband. I ate as what they
writer punctuating sentences. It is no wonder that the	ters we tend to







ic graphical tool for analyzing edance match—has become our sem.

r it striking, then, that from a the filter—as one of our most locks—should be specifically ximally poor impedance match d as much by what they attenato pass, when thinking of filfor granted that maximizing.

arlottesville, Virginia, United States

November/December 2018

the filter's rejection goes hand-in-hand with minimizing its return loss at the same frequency. Rejection by reflection is the implicit assumption in almost any con-

Experienced system designers know that we have add a price for this samplism. Filter, all los any other uncetional component, interact with the algorithm opponents both in lateral and cost of both. The filter both and the system is the state of the state of the overentianal losses filter does not actually remove here signals from the system it in its mody redirect them. The adjoints of component—asyst an amplifier ensuity of the system is the state of the system of the mixet, or an analog is-digital converter (ADC) universe or an analog is-digital converter (ADC) universe or an analog is-digital converter (ADC)—

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implicitly assumed when the litter was designed. Gai compression, escalization, or the prodictation of sparsious mixing products [1] are a common result. We have regigned caratwelses to inserting isolators or pads into our signal path, when necessary, to mitigate, or at lease soften, these effects. Isolators are, of course, bully exprusive, and band-limited, while pads attenuate the desired signals as well as the undestired ones and often reconstitute additional gain in the system.

One could argue that the mixer, amplifier, or AUC is as much to blame for this situation as the filter. But there is a difference. The mixer, amplifier, and AUC each have poor out-of-bard return less as a result of imperfect manufacturing or instate device parasitics, but the filter has poor return loss there because it was designed for this. Moreover, it was designed with great magnetic hard near-soft-defined the second state of the second state.

#### You Can Have Your Filter and a Good Impedance Match. Too

There is a better way. Filters that reject by absorption, not reflection, have been around for quite some time, but they have not found widespread use. This is possibly due to the fact that most known solutions (until recently) have suffered from a number of significant drawbacks:

- inherently limited bandwidth
- fundamental excess passband loss
   reflective neaking in the transition
- asymmetric imp

In this article, we will examine these drawbacks for a number of classic solutions. Bulk size.—or conversely, miniaturization—is an especially important aspect in many emerging applications, such as wearable technology and the Internet of Space (Ic65) [2], so we will give this characteristic special attention.

Figure 1 shows a well variety of anglenda doublet of the order, we have veregoids carryin resonance directional libers [4]. A directional filter in forto the order, we strength on the order of the complex filter interface of the order of the complex filter functions. Thus, for any given input perong of the restanding person is in advectition of the restanding person is independent, which the two irregargency for an absorptive busilesging filter, through and inducing busiless of the theory of the interface of the theory of the strength of the metmatical distribution of the theory of the strength of the metric of the theory of the strength of the metric angle are weighted, more install generally these metric shows there is not independent of the strength of the of centineters in stars. Further, the coupling strengtnete wave filter, function, this susceibly would be tunn of centineters in stars. Further, the coupling strengttion of the strength of the

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# **Backup Slides**



# **Canonical Filter Responses**



Chebyshev Type II



Legendre



Butterworth



# **Conventional Topologies**





Divide out immittance and corner frequency...

Normalized Ladder Prototype







Normalized Response




## **Even-Order Filters**



(Element values are normalized for frequency and impedance.)

- One may derive an even-order filter by allowing the last reactive element from an odd-order prototype to become zero.
- This inevitably leaves some negative, zero, or infinitely-valued elements in the bottom-most position.
- The zero/infinite components simply disappear, and the negative elements can be compensated in the usual way.



## **Even-Order Filters**



- Many even-order filter prototypes have nonunit-value normalized termination impedance.  $(g_{N+1} \neq 1)$
- An extra resistor is then required to meet the duality condition.

• 
$$R = 2/(g_{N+1} - 1/g_{N+1})$$

• If this formula gives a negative resistance, than the same transformer identities as before can be used to remove it.



## **Butterworth is its Own Inverse**

"Type-I" Butterworth Topology (*N*=5)









## **Butterworth is its Own Inverse**





# **Transmission-Line Topologies**























Must restore symmetry...





## **Coupled-Line Identities**



A NOT SO Well-Known Identity





## **Application of Coupled-Line Identity**

















