Non-Reflective Transmission-Line Filters for Gain Slope Equalization

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Abstract — **In this paper we present several topologies of simple non-reflective filters using transmission lines and resistive elements. These filters are well-matched at all frequencies, making them especially suitable for gain slope equalizers without the need for external attenuators or isolators. The application of these filters to a 2-4 GHz, ±15 dB selectable-slope equalizer for the Expanded Very Large Array is described with measured results that are in good agreement with theory.**

Index Terms — **equalizers, microwave filters**

I. INTRODUCTION

Modern microwave and millimeter-wave receivers for radio astronomy often struggle with excessive passband ripple and gain slopes. The problem is made worse by ever-widening requirements on receiver tuning range and instantaneous IF bandwidth. It is not uncommon for spectral baselines to experience output power density variations of 5-10 dB over several GHz of processed bandwidth, having obvious negative impacts on the dynamic range and A/D efficiency.

In many cases, a gain slope equalizer is needed to compensate for the intrinsic passband variation before digitization. An ideal passive slope equalizer should have no excess loss (i.e. the minimum attenuation should be 0 dB) and it should be well-matched across the entire band of interest. The simplest common form of equalizer consists of a lumped-element attenuator or a single resistive element with capacitors or inductors used to selectively mask-out the resistors over some portion of the frequency band [1]. While simple to design, these equalizers often have excess loss and poor impedance characteristics. An example is shown in Figure 1. This simple resistor-inductor combination has a 4.5 dB positive slope from DC to 10 GHz, but its excess loss of 1.5 dB is a full third as large as the slope it provides. Furthermore, it has very poor input match, only 6 dB at the low frequency end. As shown in the plot, when combined with terminations that are mismatched at the 10 dB level (not unusual in a microwave system), the effect on its intended slope characteristic can be disastrous.

Deceptively simple-looking equalizers such as these may also be difficult to implement in practice due to parasitics at microwave frequencies. Another approach is to use conventional transmission line filter topologies in which the filter elements are purposely mistuned to create a slope across the band. As these filters typically contain only lossless elements, the impedance mismatch problem is even worse, so they are usually only used in conjunction with isolators.

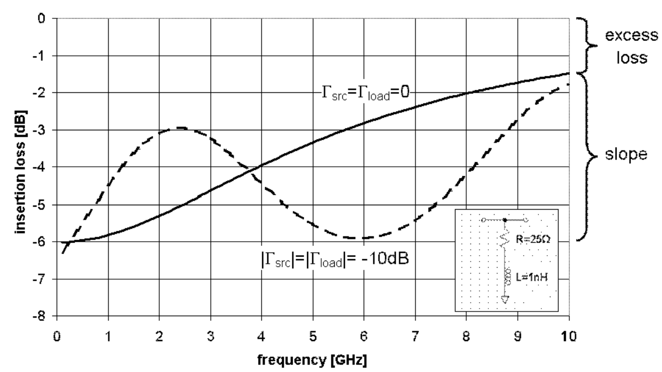

Fig. 1. Illustration of mismatch effects on a traditional lumped-element equalizer. The solid line corresponds to the designed response with perfectly matched loads, whereas the dashed line is an example of the response using 10 dB terminations at ~1 cm spacing.

In this paper we present simple non-reflective transmission line filters suitable for gain slope equalization without the need for isolators. These filters are designed to be well-matched at all frequencies independent of the slope, and have minimum excess loss. We will also describe the practical application of these filters in a 2-4 GHz, ±15 dB, selectable-slope equalizer for the Expanded Very Large Array (EVLA) radio telescope.

II. NON-REFLECTIVE FILTERS

Although not strictly necessary, it is convenient when designing transmission-line based equalizers if the frequency range occupies exactly one octave of bandwidth. This allows the maximum variation of impedance across a quarter-wave transmission line from one end of the band to the other, and thus the largest possible gain slope can be realized within the limits of the topology. Fortunately, the IF band of the EVLA is 2-4 GHz, following this convention.

A number of topologies of non-reflective filters suitable for gain slope equalization are shown in Figure 2. All transmission lines are a quarter wavelength long at the low end of the design octave. Design equations for several of these filters are given in Table I.

The filter labeled "Type A" is easily recognized as a directional coupler with matched terminations on the isolated and coupled outputs. In principle, any kind of directional coupler or hybrid can be used. However, coupled-line couplers (single-section, multi-section, or tapered) are preferable in this application because they maintain good

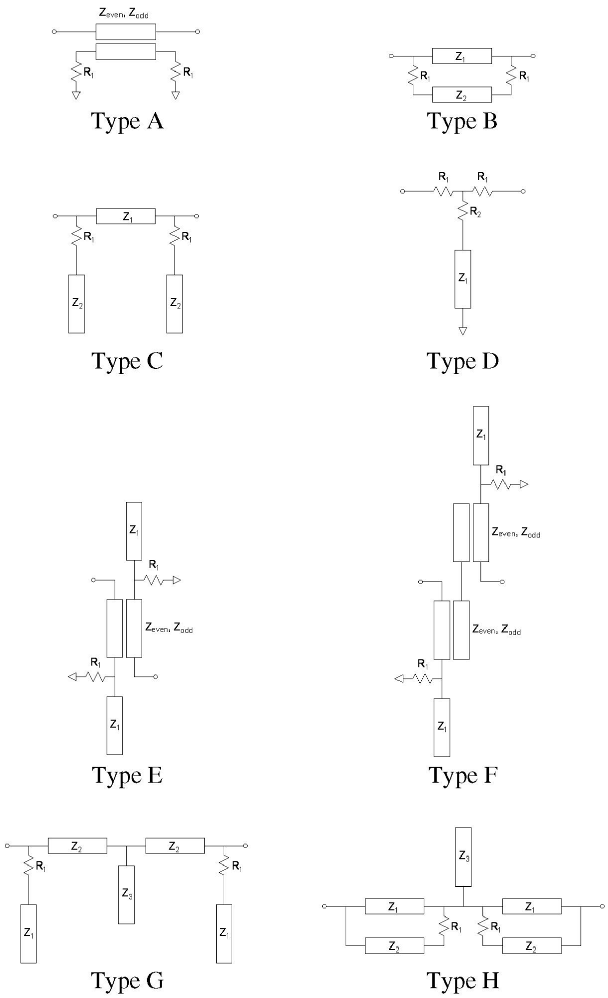

Fig. 2. Topologies for several non-reflective transmission-line filters. All transmission lines are a quarter-wavelength long at the low end of the design octave. Design equations are given in Table I.

impedance match even outside the maximally coupled bandwidth, whereas branchline and Lange couplers for example do not.

Filter B consists of two uncoupled transmission lines with series resistors in one of the paths. When properly tuned, this structure has perfect impedance match (s_{11}=0) at all frequencies. In principle, any finite positive slope can be realized, however the line impedances become extreme for slopes greater than about 6 dB.

Type C illustrates a filter which is practical for positive slopes much larger than Type A or B. The return loss is not theoretically infinite like the filters above, but is always greater than 15 dB at all frequencies.

Type D is the first filter here that can generate negative slopes over an octave band. It is also the first with any excess loss, up to a maximum of 3.5 dB for very large slopes. It is worth noting that as the slope gets larger, the line impedance, Z_1, gets smaller. For the largest slopes, it may be easier to implement if the stub and its resistor, R_2, are split into two

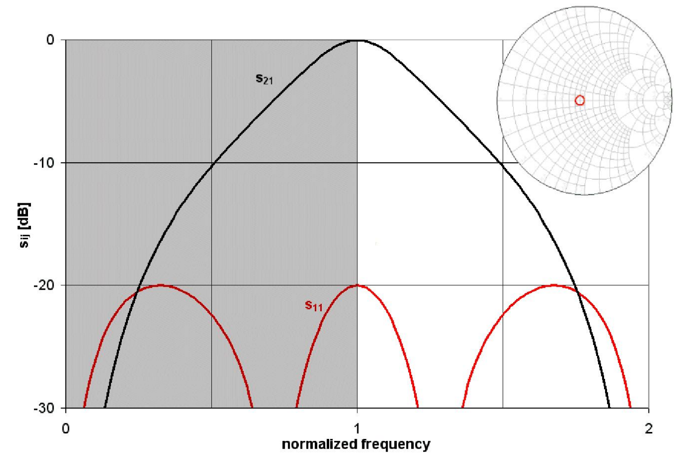

Fig. 3. Typical response of filter E. The slope over one octave is theoretically infinite while maintaining better than 20 dB input match at all frequencies.

equal stubs having twice the impedance.

Filters E and F can be made to have infinite attenuation at the top of the design octave, making them suitable for arbitrarily large negative slopes. The excess loss of filter E, while not identically zero, is nonetheless extremely small. A plot of the theoretical response of filter E for one possible tuning is shown in Figure 3. However, it is difficult to implement in practice due to the tight coupling required. Filter F can be realized with less tightly coupled lines, and has zero excess insertion loss, but requires very high impedance stubs for optimal matching.

Finally, filters G and H have infinite attenuation at the bottom of the design octave, making them suitable for arbitrarily large positive slopes.

Exact design equations have been derived for filters A through E, and are given in Table I. These solutions are optimal in the sense that they maximize the minimum return loss over all frequencies for a given octave slope (or for a given passband width). Curiously, these solutions also each result in s_{11} tracing a perfect circle on the Smith Chart – a fact which can be used to simplify their derivation.

III. EVLA 2-4 GHz Slope Equalizer

The non-reflective filters described above were used to construct a slope equalizer for the IF system of the EVLA. Based on measurements of the prototype instrumentation for that telescope, it was realized that depending on the receiver used and the LO frequency selected, the 2 GHz IF band could experience slopes of up to 15 dB in either direction [2]. This far exceeded the specifications required to get the desired efficiency from the digitizers.

It was decided that a programmable equalizer would be designed using a switch-network of passive filters with slopes ranging from -15 dB to +15 dB in 2 dB increments. As shown in Figures 4 and 5, filters A through D cover almost this entire range using standard microstrip technology with reasonable

TABLE I: Design Equations for Non-Reflective Filters

Type	optimal matching conditions (impedances normalized)	RL_{min} [dB]	IL_{min} [dB]	octave slope [dB]
A	$\rho = \frac{(2-T^2)+2\sqrt{1-T^2}}{T^2}$; $R_1 = 1$; $Z_{even} = \sqrt{\rho}$; $Z_{odd} = \frac{1}{\sqrt{\rho}}$	∞	0	$+10\log\left(\frac{1}{T^2}\right)$
B	$R_1 = \frac{1}{1-T^2}$; $Z_1 = \frac{1}{T}$; $Z_2 = \frac{T}{1-T^2}$	∞	0	$+10\log\left(\frac{1}{T^2}\right)$
C	$Z_2 = \frac{Z_1}{Z_1^2 - 1}$; $2R_1^2 = Z_1 Z_2$	$10\log\left((2R_1+1)^4\right)$	0	$+10\log\left(\frac{(2R_1+1)^4}{8R_1^2(2R_1^2-1)}\right)$
D	$R_1 = \frac{1}{2}(1-T)$; $R_2 = \frac{T(3-T)}{4(1-T)}$; $Z_1^2 = \frac{T(3-T)^2}{16(1-T)^2}$	$10\log\left(\left(\frac{3-T}{1-T}\right)^2\right)$	$10\log\left(\frac{(3-T)^2}{4}\right)$	$-10\log\left(\frac{1}{T^2}\right)$
E	$\rho = \frac{3+\gamma+2\sqrt{2(1+\gamma)}}{1-\gamma}$; $Z_1 = \frac{(1-\gamma)\sqrt{\rho}}{2\gamma(\rho+1)}$; $R_1 = 1$; $Z_{even} = \sqrt{\rho}$; $Z_{odd} = \frac{1}{\sqrt{\rho}}$	$10\log\left(\frac{1}{\gamma^2}\right)$	$10\log\left(\frac{(\rho+1)^4}{16\rho(\rho-1)^2}\right)$	$-\infty$

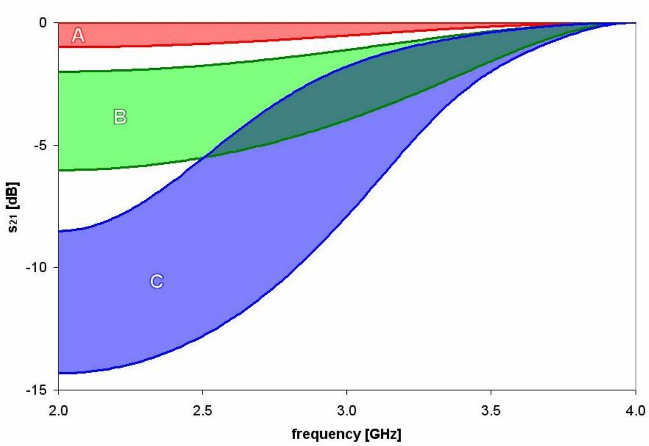

Fig. 4. Plot of the practical slope ranges for filters A, B, and C. These are the slopes that are readily achievable with optimal matching, with line impedances between about one-half and twice Z_0, and with a maximum coupling factor of 2.5.

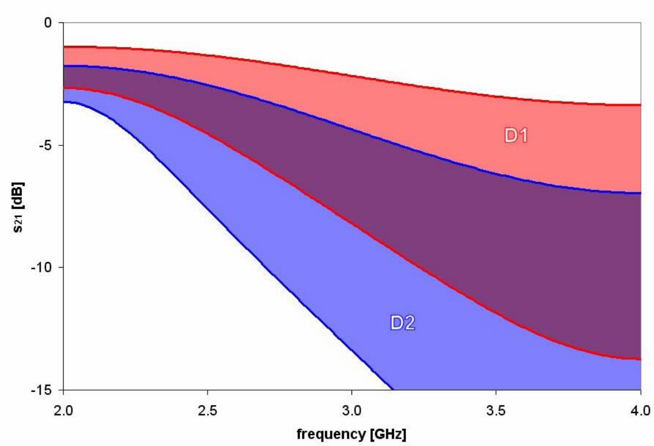

Fig. 5. Plot of the practical slope ranges for filter D with 1 stub (D1) and 2 stubs (D2). These are the slopes that are readily achievable with optimal matching, and with line impedances between about one-half and twice Z_0.

feature sizes. Since the filters are all well-matched and low loss, they can be easily cascaded to fill in the gaps and achieve even larger slopes.

The equalizer was fabricated as a four-layer PCB on Rogers 4003 high frequency laminate. A photograph is shown in Figure 6. The transmission lines were drawn on the top layer and the resistive elements were realized using inexpensive surface mount components. The 16-rung switch ladder was implemented using two SP2T and four SP8T surface mount switches. Switch control and bias lines were routed on a lower metal layer. The board includes two stages of amplification to offset the mid-band loss of passive sloping filters, and a different fixed attenuator was placed in each filter path so that the mid-band gain would be approximately the same in all states. The goal was to make the equalizer as transparent as possible to the rest of the system.

It was critical to select active components with the flattest possible gain curve over the design bandwidth. With two amplifiers and four switches in each RF path, small ripples add up quickly to significant deflections from the desired

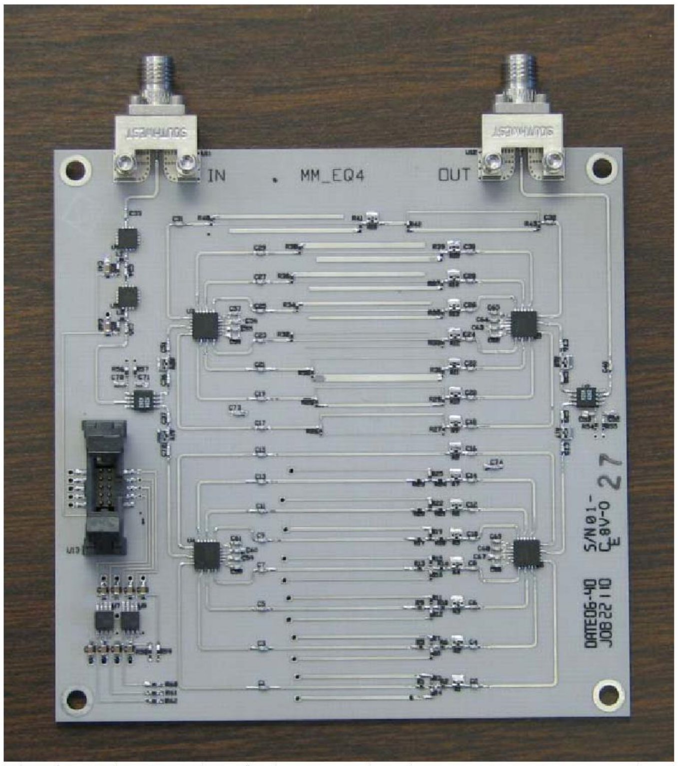

Fig. 6. Photograph of the completed 2-4 GHz EVLA slope equalizer.

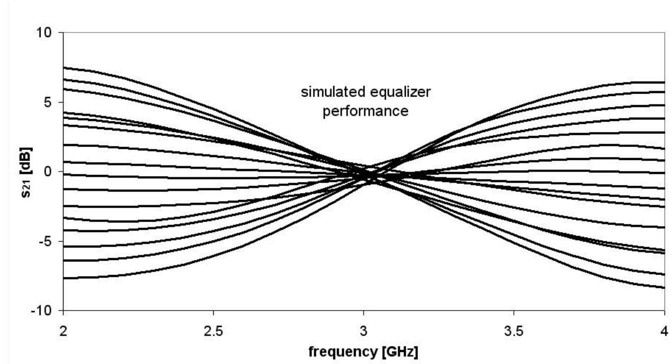

Fig. 7. Simulated response of the EVLA 2-4 GHz slope equalizer.

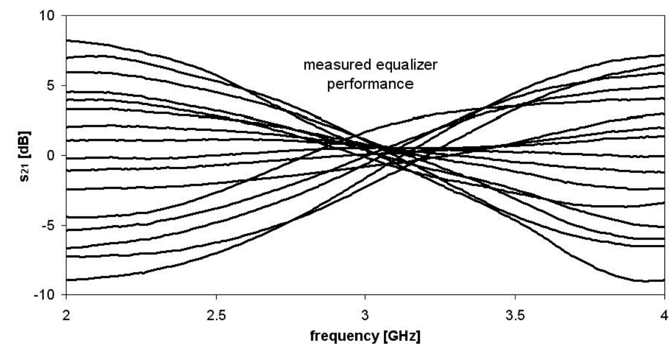

Fig. 8. Measured response of the EVLA 2-4 GHz slope equalizer.

slope. A careful analysis was also performed on the loss of the microstrip feeder lines, coupling capacitors, and SMA launchers as a function of frequency. This predicted a net excess slope of about -2 dB. A compensating +2 dB bias was thus built into the slopes of each filter. A prediction of the equalizer performance with all of this taken into account is shown in Figure 7.

The performance of the equalizer was measured using a Vector Network Analyzer, and the results are shown in Figure 8. The gain curves are smooth and have an average gain of approximately 0 dB, with evenly spaced slopes between -17 dB and +16 dB. Although the targeted slope range was exceeded by about 10%, the overall characteristic is in good agreement with the prediction.

IV. Conclusion

Several topologies of non-reflective transmission-line filters have been described. These designs have been used to build a programmable gain slope equalizer for the Expanded Very Large Array in the 2-4 GHz frequency range, with slopes ranging from -17 dB to +16 dB. Measured results indicate good agreement with theory.

While the focus of this paper has been on slope equalization, it is worth noting that non-reflecting filters such as these could have advantages in many systems where good impedance match is required out-of-band. For example, the authors have used some of these same topologies as on-chip IF filters in mixers where a standard reactive filter would adversely interact with the RF/LO circuitry [4].

Acknowledgement

The authors wish to acknowledge the assistance and support of their colleagues at both the Array Operations Center and the Central Development Laboratory at the NRAO. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

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