

# Passive Enhancement of Resonator Q in Microwave Notch Filters

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**Abstract** — The lumped-element bridged-T notch filter concept is extended to reciprocal distributed-element microwave filters. A prototype microstrip bridged-T notch filter employing single-mode resonators is described that enhances the effective resonator  $Q_u$  by a factor of 325, while a different microstrip filter topology with a triple-mode resonator is described that enhances the effective resonator  $Q_u$  by a factor of 89. The new notch filters can be either partly reflective or fully absorptive within the stopband. Additional enhanced- $Q_u$  notch filter topologies, such as a hybrid-coupler notch filter, that include at least two resonances and at least two signal paths are suggested.

## I. INTRODUCTION

Currently, there is significant interest in notch filters for use in advanced communication systems [1], [2]. A notch filter is used to remove a narrow band of frequencies from the signal path of a receiver or transmitter. For a conventional, “single-transmission-zero” notch filter, the maximum attenuation, or notch depth, occurs at a single frequency midway between the specified edges of the lower and upper passbands, and the selectivity can be described as the ratio of the notch depth to the bandwidth between the edges of the passbands. The unloaded Q ( $Q_u$ ) of the filter’s resonators limits both notch depth and selectivity. Since  $Q_u$  is generally proportional to resonator volume, the desire for a deeper, more selective notch is at odds with the drive towards miniaturization.

About seventy years ago, Hendrik Bode discovered a lumped-element circuit that provides a way around this seemingly unavoidable tradeoff between notch filter size and performance. Bode found that by splitting the signal between two passive circuit paths, designed such that the resistance and reactance of the paths balance (i.e., are equal) at a particular frequency, quasi-infinite attenuation could be achieved at the frequency of the impedance balance, independent of the loss in the filter components [3], [4]. Because this circuit calls for one signal path to “bridge” a second signal path consisting of a T-network of impedances, it is called a “bridged-T” notch filter. Although Bode’s filter provides substantial benefits, it is not discussed in standard filter texts (except for an indirect reference in [5]), and, consequently, it is not well known.

The purpose of this paper is to extend Bode’s bridged-T notch filter concept to reciprocal circuits that include distributed elements. It is demonstrated that, for distributed element circuits, the concepts of attenuation balance and phase cancellation [6] can take the place of Bode’s impedance balance concept. The result is essentially the passive enhancement of resonator effective  $Q_u$  ( $Q_{u,eff}$ ). A microstrip bridged-T topology is used to illustrate how one can obtain quasi-infinite attenuation at single frequencies using passive lossy distributed components. Also, it is shown that the technique can be generalized to other topologies that include at least two resonances and at least two signal paths.

## II. ENHANCED- $Q_U$ PASSIVE NOTCH FILTERS

The passive two-path distributed-element enhanced- $Q_u$  notch filter concept is sketched in Fig. 1. A portion of the input signal is coupled through a bandpass filter to the output, while the remaining portion of the input signal is coupled through a bandstop filter to the output. If, at a certain frequency (or frequencies), the two portions of the signal arriving at the output are of the same magnitude but an odd multiple of  $180^\circ$  out of phase with each other, then the two will cancel and infinite attenuation will result.

However, it is easy to see that the number of signal paths between input and output need not be limited to two. Any number of signal paths (greater than one) between the input and the output should yield comparable results, provided that the signals from the various paths cancel each other at the output at some frequency or frequencies.

Examples of reciprocal filters with two signal paths, and with more than two signal paths, will be given below.

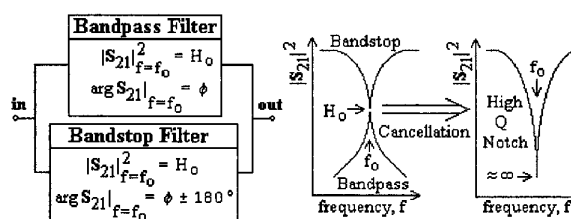


Fig. 1. Distributed-element enhanced- $Q_u$  notch filter concept.

### A. Microstrip Bridged-T Notch Filter

An example of a two-signal-path enhanced- $Q_u$  notch filter is the distributed-element bridged-T notch filter. A conceptual diagram of such a filter is shown in Fig. 2(a), where one portion of the input signal is coupled through a bandpass resonance to the output, while the remaining portion is routed to the output through a single-resonance notch filter. A corresponding idealized circuit schematic is shown in Fig. 2(b), where the transformer turns ratio,  $n$ , is

$$n^2 = R / Z_0 = 2\pi f_0 L / (Z_0 Q_u), \quad (1)$$

with  $R$  the resistance,  $L$  the inductance,  $f_0$  the resonant frequency, and  $Q_u$  the unloaded  $Q$  of each resonance. The constituent notch filter consists of a "delay-line" transmission line of characteristic impedance  $Z_0$  coupled to a notch resonance midway along its length. To achieve signal cancellation at frequency  $f_0$ , both resonances are tuned to resonate at  $f_0$ , the delay line is about a half-wavelength long at  $f_0$ , and the attenuation at  $f_0$  is about the same through both signal paths. The layout and photo of a microstrip realization appear in Figs. 2(c) and (d), where both resonators are open-circuited half-wavelength lines that are partially parallel-coupled to the  $50 \Omega$  delay line.

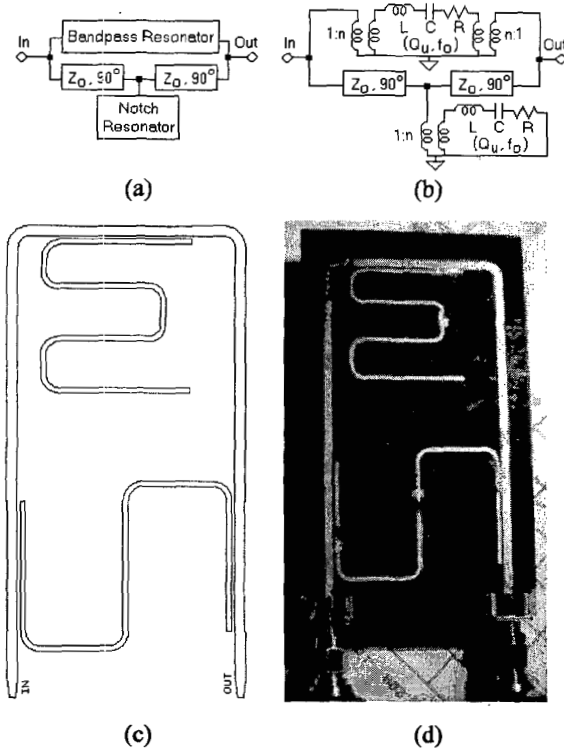


Fig. 2. Distributed bridged-T notch filter (a) concept, (b) circuit schematic, (c) microstrip layout, and (d) realization.

The prototype was constructed using SMA connectors and a 98.43 mm x 57.15 mm Taconic TLT-8-0310-CH/CH substrate with a dielectric thickness of 0.78 mm, relative dielectric constant of 2.55, dielectric loss tangent of 0.0006, and copper thickness of 0.036 mm. The delay line width is 2.06 mm and the resonator line width is 1.02 mm, providing impedances of 51.3 and 76.7 ohms, respectively. The parallel-coupled line sections are 25.02 mm long with a 0.51-mm coupling gap and are connected by 59.31-mm lengths of delay line. The bandpass and notch resonator line lengths are 121.54 mm and 122.40 mm, respectively. Fig. 3 shows the measured filter response: a center frequency of 852 MHz, notch depth of about 58 dB, and relative 3-dB bandwidth ( $bw_{3dB}$ ) of 1.55%. The bandpass and notch resonators have measured  $Q_u$ 's of about 155 and 134, respectively, while the prototype filter's effective  $Q_u$  is 50,400, which represents effective  $Q_u$  enhancement by a factor of more than 325.  $Q_u$  is calculated from measured band-reject responses using:

$$Q_u = \left| \frac{f_0 f_1}{f_1^2 - f_0^2} \right| 10^{L_0/20} \sqrt{\frac{10^{-L_1/10} - 10^{-L_0/10}}{1 - 10^{-L_1/10}}}, \quad (2)$$

where  $L_0$  and  $L_1$  are attenuation values at center frequency  $f_0$  and frequency  $f_1$ . When calculating  $Q_u$  of individual resonators, delay line loss is subtracted from  $L_0$  and  $L_1$ .

Resonator  $Q_u$  still limits notch selectivity through (1). To realize greater selectivity (smaller values of  $n$  and  $bw_{3dB}$ ), the bandpass resonator can be replaced with a bandpass resonator-amplifier-resonator cascade (as in [1] and [6]) and/or the effective value of  $Z_0$  can be increased using impedance transformations (as in [7] & [8]). For example, assuming a lossless delay line and equal source and load impedances,  $R_S$  and  $R_L$ , when  $Z_0 = R_S$  then  $bw_{3dB} \approx 2.53/Q_u$ , but when  $Z_0 = 2R_S$  then  $bw_{3dB} \approx 2/Q_u$ .

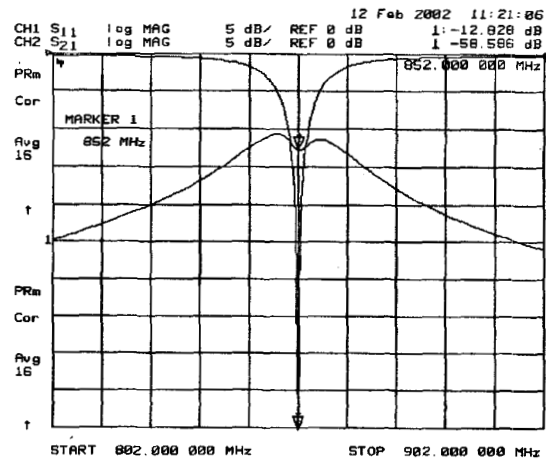


Fig. 3. The measured insertion and return loss response of the microstrip bridged-T notch filter.

### B. Triple-Mode Microstrip-Resonator Notch Filter

The triple-mode half-wavelength microstrip-resonator circuit in Fig. 4 is an example of an enhanced- $Q_u$  notch filter with more than two signal paths. The diagram and schematic in Figs. 4(a) and (b), corresponding to the microstrip layout in Fig. 4(c), show there are five possible signal paths between the input and output, with resonances providing three distinct bandpass paths and the transmission line providing delay paths. In this case,  $n$  is much more complicated than given in (1).

The prototype in Fig. 4(d) uses the same materials, line widths, and coupling gaps as the filter in Fig. 2(c), except that the parallel-coupled-line sections are 20.32 mm long and are connected by 80.77-mm lengths of delay line. Fig. 5 shows the measured filter response: a center frequency of 852 MHz, notch attenuation of 51 dB, and  $bw_{3dB}$  of 1.43%. For this circuit, individual resonance  $Q_u$ 's cannot be calculated using (2) and the notch center frequency is offset from  $f_o$ . Simulations suggest that the resonances had  $Q_u$ 's of 250 and  $f_o = 852.5$  MHz. The prototype's effective  $Q_u$  is about 22,300, which represents an effective  $Q_u$  enhancement by a factor of about 89. Fig. 5 shows smaller  $bw_{3dB}$  and stopband reflection than simulations of the circuit of Fig. 4(b), possibly due to coupling between resonant modes caused by lack of three-way symmetry.

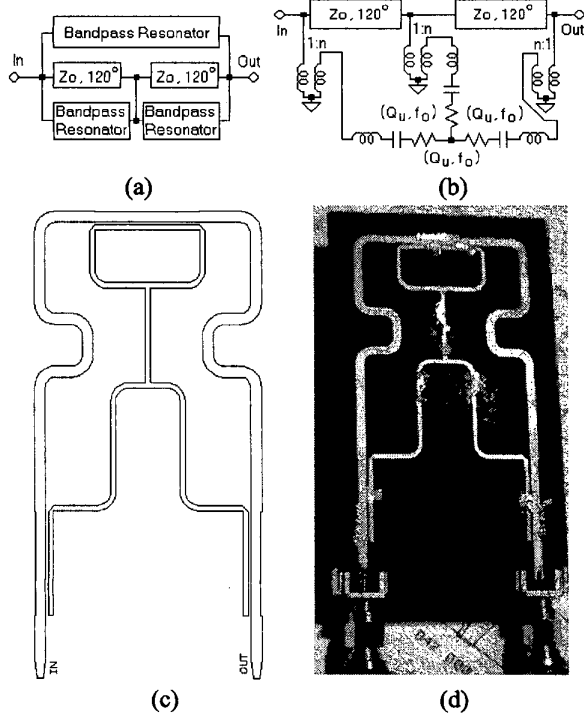


Fig. 4. Triple-mode-resonator notch filter (a) concept, (b) circuit schematic, (c) microstrip layout, and (d) realization.

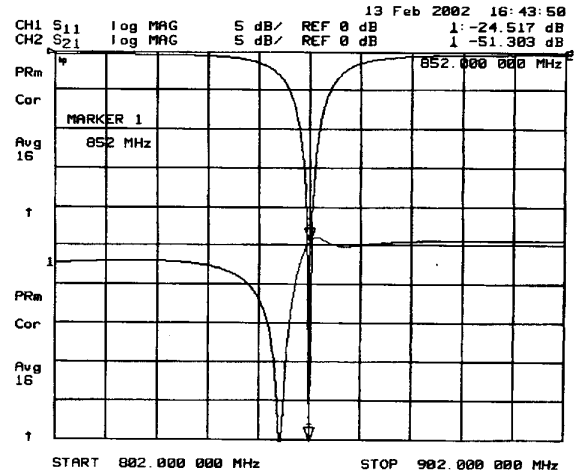


Fig. 5. The measured insertion and return loss response of the triple-mode microstrip resonator notch filter.

### C. Discussion of Tuning and Experimental Results

The fine tuning of both prototypes was done in a makeshift fashion, with a few small strips of copper foil attached with conventional epoxy to the main transmission line to tune the return loss, to the coupled sections of the resonators to tune the coupling (notch depth & bandwidth), and to the uncoupled sections of the resonators to tune the resonant frequencies (notch center frequency). While circuit simulations had suggested that notch attenuation might be extremely sensitive to filter parameters, the fact that the anticipated results could be realized using such rudimentary tuning is evidence of the robust nature of the proposed  $Q_{u,eff}$ -enhancement concept. Notch depths of 40 dB were relatively easy to achieve in practice starting from resonator notch depths of less than 10 dB, and seemed to be limited only by resonant frequency tuning accuracy. Resonator  $Q_u$  did not limit notch depths, but did limit minimum  $bw_{3dB}$  (or minimum effective couplings). Still, 3-dB bandwidths of about 1.5% were achieved while realizing notch depths of over 50 dB.

In both prototypes and simulations, the resonant frequencies,  $Q_u$ 's, and delay-line couplings of individual resonances were determined by detuning other resonances with a probe and measuring the resulting band-reject responses. Initial tuning attempted to match simulated and measured responses of individual resonances. Then the overall response was fine-tuned. The return loss (RL) of both prototypes could be tuned to provide a range of performance in the stopband, from being somewhat reflective (13 dB RL) to absorptive ( $\geq 24$  dB RL), without adversely affecting the attenuation characteristic.

#### D. Alternative Enhanced- $Q_u$ Passive Notch Filters

The preceding results suggest that signal cancellation can occur in a variety of circuit topologies. Investigations with a circuit simulator [9] verified this. Eight different two-resonator topologies with at least one delay path were simulated, both with and without inter-resonator coupling, and all exhibited responses similar to the examples above.

One such topology is shown in Fig. 6, where two resonances with equal  $Q_u$  and equal resonant frequency,  $f_0$ , are coupled to a 3-dB,  $90^\circ$  hybrid coupler (or 3-dB directional coupler) via transformers with turns ratio,  $n$ , as in (1), and where the coupler is designed to have each of its four ports terminated in impedance  $Z_0$ . The resonances could just as easily be distributed, rather than lumped, and the transformers could be replaced with any suitable means of achieving the requisite coupling. Assuming an ideal hybrid with its impedance matched to the source and load impedances ( $Z_0=R_S=R_L$ ), the relative 3-dB bandwidth is

$$bw_{3dB} \cong \frac{2}{Q_u}. \quad (3)$$

Although the filter described by Fig. 6 (and equations (1) and (3)) was developed independently, a subsequent literature search has revealed similar suggestions by others [10], [11].

#### III. CONCLUSION

The lumped-element bridged-T notch filter technique is extended to distributed-element microwave notch filters, in which the concepts of attenuation balance and phase cancellation are substituted for the concept of impedance balance. The new technique effectively enhances resonator  $Q_u$ , offering a passive reciprocal means to further miniaturize microwave notch filters. Effective  $Q_u$  enhancement is demonstrated for a variety of filter topologies that employ at least two resonances and employ at least two signal paths. In the examples, the minimum relative 3-dB bandwidths are reduced, and effective  $Q_u$ 's are increased, by about two orders of magnitude. It is expected that fixed and mechanically or electronically tuned versions of such filters will be of practical use in advanced communication systems.

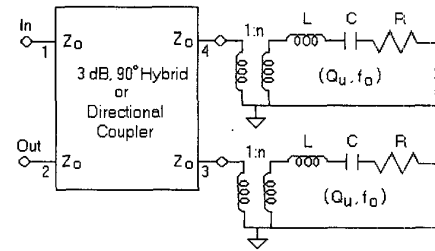


Fig. 6. Conceptual diagram of an enhanced- $Q_u$  notch filter employing a 3-dB,  $90^\circ$  hybrid coupler.

#### ACKNOWLEDGEMENT

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