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FILTERS FOR STOCHASTIC COOLING OF LONGITUDINAL BEAM EMITTANCE*

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Introduction

The shorted stub filter (SSF) has been used extensively to provide the electronics gain shaping for stochastic cooling of longitudinal beam emittance.[1-3] Figure (1a) shows a schematic diagram of the SSF. The repetitive notch of this filter results from the cancellation of the incident signal by the reflected signal at frequencies where the cable electrical length equals an integer number of half wavelengths. Variations in notch depth of the SSF have been approximately compensated by a rather complicated system.[4] Dispersion of the notch frequency resulting from variation of the phase velocity can also be approximately corrected using tuned imperfections in the shorted cable.[5] Dispersion due to imperfections in the coaxial cable can be quite significant and can only be compensated for by costly construction techniques.[4]

This paper describes another type of notch filter. Although this filter has been mentioned previously,[6] this analysis will demonstrate the advantages of this filter in providing small notch dispersion and other properties necessary for stochastic cooling systems. Because this filter uses only forward signals, it is quite insensitive to imperfections in cables and components, and can therefore be constructed from commercially available components.

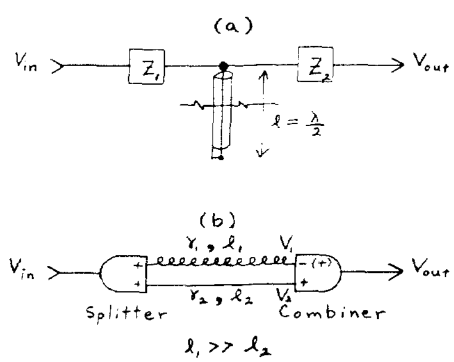

Figure 1(a). Schematic diagram for the commonly used shorted stub notch filter, (b) schematic diagram of the Basic Correlator Filter, with signal (V_1) from a long length (ℓ_1) of low attentuation cable and signal (V_2) from a short length (ℓ_2) of high attenuation cable combined in a 180°(-) or 0°(+) combiner.

Description of the Basic Correlator Filter(BCF)

The BCF system is presented schematically in Fig. (1b). This filter uses the correlation between the different delay time of two cables to determine the repetitive notch frequency spacing, f_o. The voltage transfer, $T(f)$, for this filter is given by

$$T(f) = \frac{1}{2} e^{-\gamma_2 \ell_2} \left[1 \, (\mp) \, e^{-(\gamma_1 \ell_1 - \gamma_2 \ell_2)}\right] \qquad (1)$$

where $\gamma = \alpha + i\beta$, the cable propagation constant and ℓ = the cable length.

The negative sign corresponds to a 180° combiner and the positive sign to a 0° combiner being used in Fig. (1b). To zeroth order, $\gamma = i\beta_o = i\frac{2\pi f}{V_o}$, where V_o is the phase velocity of the cable. Figure (2) shows the phasor diagram for Eq. (1) and indicates that notches will occur whenever the two signals being combined are anti-parallel. This occurs at a frequency spacing

$$f_o = \left(\frac{\ell_1}{V_{o1}} - \frac{\ell_2}{V_{o2}}\right)^{-1} = (t_1 - t_2)^{-1} \qquad (2)$$

the inverse of the difference in delay time for the two signals. For the 180° combiner, notches (minima of $T(f)$) will occur at $f = nf_o$ and peaks (maxima of $T(f)$) will occur at $f = \left(n + \frac{1}{2}\right) f_o$, for $n = 0,1,2....$ For the 0° combiner, the peaks and notches are interchanged. Figure (3) shows the magnitude and phase of $T(f)$ for a BCF with f_o = 1 MHz and for both signs of the combiner. The notch depth (ratio of peak to valley $|T(f)|$) is controlled by the degree of cancellation of the two signals.

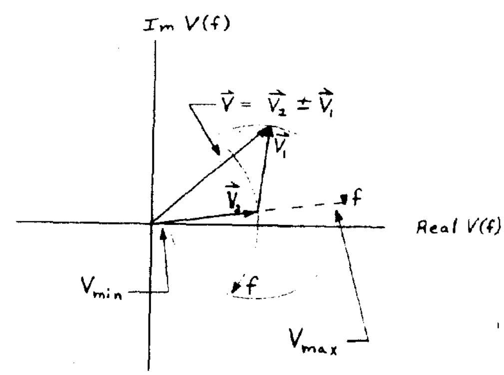

Figure 2. Phasor Diagram for the Basic Correlator Filter shown in Fig. (1b). Also shown is the influence of the attenuation of the V_1 signal on the notch (V_{min}) and the influence of the phase dispersion of signal V_2 on the phase at the notch.

Compensated Correlator Filter (CCF)

Real cables with attenuations that vary with frequency will have exact cancellation at only one frequency, unless $\alpha_1(f) = \alpha_2(f)$. In order to maintain 30db deep notches, the two signals must be within 0.5db of each other. In addition to notch depth variations, there will also be dispersion of the frequency where the notches occur resulting from the different phase dispersion for the two cables. To first order, the attenuation and phase for transmission cables can be expressed as[7]

$$\alpha = \alpha_c + \alpha_d \text{ and } \beta = \beta_o + \alpha_c$$

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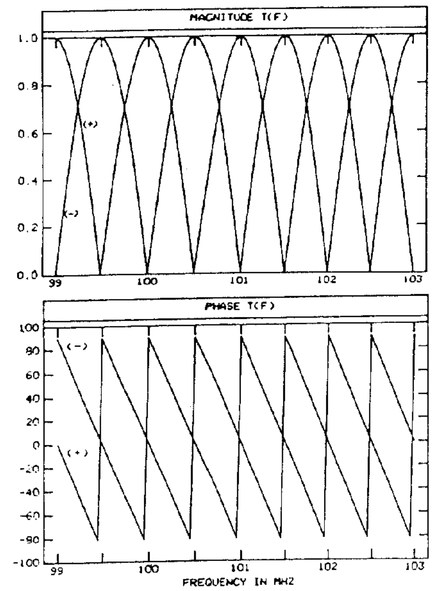

Figure 3. Magnitude and phase of T(f) for the BCF with 180° (-) and 0° (+) combiner.

where α_c = the attenuation due to conductor losses and α_d = the attenuation due to dielectric losses. Clearly the notch dispersion can be eliminated if

$$\alpha_{c1} \ell_1 = \alpha_{c2} \ell_2 \tag{3}$$

and the notch depth variation avoided if

$$\alpha_1 \ell_1 = \alpha_2 \ell_2 \tag{4a}$$

or

$$\alpha_{d1} \ell_1 = \alpha_{d2} \ell_2 \quad \text{plus Eq. (3)} \tag{4b}$$

The zero notch dispersion condition, Eq. (3), is easily achieved by using small diameter cable with a high resistivity conductor (e.g. nichrome). This CCF has been demonstrated with a prototype filter built by Argonne National Lab. for the FNAL $\bar{p}$-source, using RG-178 for the high loss cable and about 400 m of RG-333 for the low loss cable. The notch measured dispersion

$$\delta = \frac{f_n - nf_o}{nf_o} \tag{5}$$

where f_n is the measured notch frequency for the n-th notch with frequency spacing f_o, is presented in Fig. (4). The notch repetition frequency was 0.63 MHz (f_o) and the measured notch dispersion had an rms value of $\pm 3 \times 10^{-6}$ for a bandwidth of 0.2 to 2.0 GHz. This dispersion was dominated by the measured phase unbalance of the splitters and combiners.

Satisfying the notch depth condition, Eq. (4), is more difficult to achieve because the dielectric loss tangents of materials have only descrete values and changes in the loss tangent also imply a change in the phase velocity of the cable. However, combining different materials can yield adequate matching to achieve greater-than-30db deep notches over reasonable frequency bands. Figure (5) shows the calculated notch depths for the CCF, shown in Fig. (3), with a commercially available high resistivity cable (O.D. = 0.141") but with an assumed

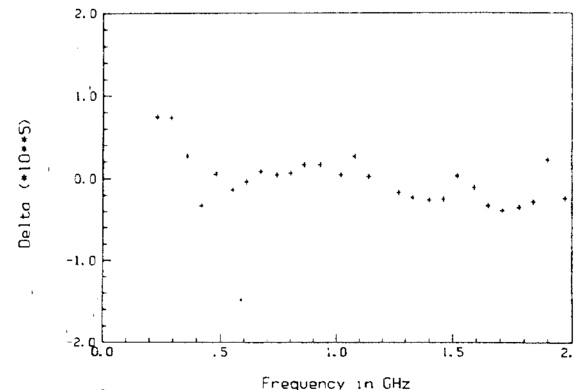

Figure 4. The measured notch dispersion for a prototype CCF with notch dispersion compensated for. Frequency spacing for the notch had f_o = 0.63 MHz.

dielectric material containing 35% nylon and 65% teflon. Without this composite dielectric, the notch depth would have varied from 30db to 9db over the 1-2 GHz band for the commercially provided teflon dielectric. In practice the notch depth variations will be limited by the magnitude unbalance of combiners/splitters and other components. However, components with unbalance less than 0.2db are readily available, permitting notch depths greater than 30db to be easily obtained.

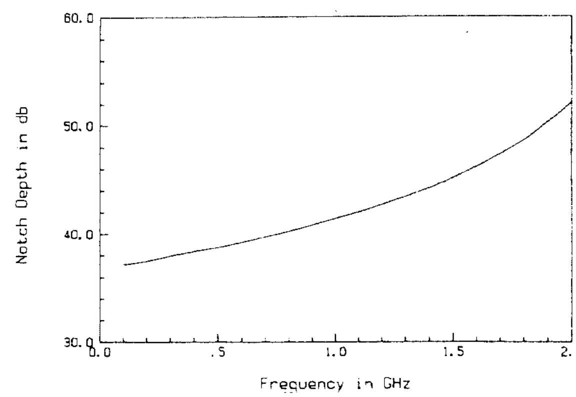

Figure 5. Calculated notch depth (ratio of peak to notch of T(f)) for a model CCF with notch dispersion and notch depth compensation.

One remaining problem of the CCF is the variation of the magnitude and phase of T(f) at the notch position resulting from the $e^{-\gamma_2 \ell_2}$ factor in Eq. (1). The variation in magnitude which, although not serious (also a problem for the SSF), reduces the effective cooling from the upper part of the frequency band. This can easily be compensated using commercially available matched components to attenuate the lower frequencies more than the high frequencies.[8] In some cases the uncorrected filter may actually counter the frequency response of pickups. The phase variation at the notch is only somewhat worse than the phase variation due to the transmission cable from pickup to kicker, because the delay time $t_1 \approx \tau_{rev}$ (the revolution period of the ring). The phase variation, again not serious, can be compensated by a tuned imperfection in the transmission cable[5] or by using a cable with opposite dispersion.[7] This latter solution has the advantage of using commercially available matched components.[8]

Finally the total signal attenuation in T(f), even at the peaks, can be quite large (≈ 30db) due to the long cables required for some systems. Although this is not a problem for CCF's used to filter small signals, this attenuation (both for CCF and SSF) is intolerable for filtering high level signals.[9] The principles of the CCF discussed here are directly applicable to systems with the long cable replaced by a superconducting coaxial cable.[10] In this case, the insensitivity of the CCF to cable imperfections will be quite an important advantage over the SSF.

Conclusions

We have demonstrated that a new type of notch filter can provide a high precision (low dispersion) filter which can satisfy most of the requirements for stochastic momentum cooling systems. The major advantage of this filter is that it can be built largely from commercially available matched components, simplifying construction and reducing the cost of the filters. Because only forward signals are used in this filter, the filter is quite insensitive to cable imperfections such as might be obtained with superconducting transmission cables.

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