CORRELATOR FILTERS FOR FEEDBACK AT SRS AND NSLS*

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Introduction

In order to amplify signals that are produced by an oscillating beam, it is desirable to first reject that part of the signal produced when the beam is not oscillating. A correlator filter [1,2,3,4] can attenuate by 45-65 dB the signal of a stable beam while reducing the oscillation signal by only 3-6 dB. Compared with other means of achieving this result, a correlator offers the advantages of at least 200 MHz working bandwidth and broadband matching to 50 ohms at input and output. Both practically and conceptually, it is a very simple device, consisting of two pieces of transmission line, a 0° power splitter and a 180° power splitter. An input signal to the filter is divided into two identical signals by the 0° splitter; these two signals are sent through two transmission lines of different length but equal attenuation and dispersion characteristics. One signal is then electrically subtracted from the other by recombination in the 180° splitter. With commercially available components, this delay and subtraction can be done with 0.1%-0.5% precision. To this accuracy, the output of a correlator filter in time and frequency domains may be written

$$V_{out}(t)= (V_{in}(t)-V_{in}(t-T))/\sqrt{2}$$

$$V_{out}(\omega)=-i\sqrt{2}\ \exp(i\omega T/2)\ \sin(\omega T/2)\ V_{in}(\omega)$$

where T is the net delay time, normally set equal to the revolution period of the storage ring. A stable beam produces identical signals on subsequent turns, and would ideally produce no output from the filter. The filter output is proportional to the difference in signals on subsequent turns.

Application to the SRS and NSLS X-Ray Rings

Correlator filters have been built for the Daresbury SRS storage ring, NSLS booster synchrotron, and NSLS X-ray ring, with net delay times of 320 nanoseconds, 95 nsec, and 567 nsec, respectively. The RF frequency is 500 MHz in the SRS and 53 MHz in the NSLS rings. All were made using 7/8" foam dielectric transmission line for the long delay line. To compensate [2] for losses in the long delay line, each filter used a piece of RG-58C cable for the shorter attenuation matching line. The 0° and 180° combiners used were Anzac models T-1000 and H-81-4. The NSLS filters were intended for the frequency range 50-250 MHz, while the SRS filter was to be used in the range 250-750 Mhz. After the filters were optimized empirically, the characteristics of the individual components were measured using Hewlett-Packard 8573A and 3577A network analyzers. Optimization of the X-ray ring filter showed that best results were obtained with a 628 nanosecond length of Andrew LDF-5-50 line. Its attenuation is 0.24 dB at 0 Hz and 3.03 dB at 200 MHz. The maximum phase error is 0.4° with respect to an ideal delay. The phase error alone would limit filter performance to 43 dB rejection unless compensated. An uncompensated 3 dB insertion loss would give no better than 8 dB rejection. Figure 1 shows the phase and amplitude of a 61 nanosecond length of RG-58C compared to the 7/8" cable, and referred to a 567 nsec delay. The attenuation varies by about 0-0.2 dB, from 0 to 200 MHz. From 60 to 200 MHz, the mismatch in attenuation is 0.0-0.1 dB, so one would expect to attain rejection notches deeper than 40 dB in this frequency range.

The average mismatch in attenuation is not 0 dB for the best performance, but about 0.1 dB. This is because the H-81-4 combiner has an output asymmetry of about 0.1 dB in the frequency range 60-200 MHz, as shown in Figure 2. This asymmetry cancels the mismatch of the cables. The deviation from linear phase variation reaches a maximum of 0.7° at 20 MHz. The relevant frequency range for the Daresbury correlator is 250-750 MHz. The H-81-4 deviates from linear phase variation by only 0.25° peak to peak, while the attenuation varies by 0.2 dB in this range. The symmetry of the T-1000 0° splitter is very accurate; the two outputs are equal to within .04 dB and .2° in the range 0-700 MHz. The NSLS X-ray filter has 50 dB minimum notch depth and 15 KHz error in notch frequencies, from 80-200 MHz. Below 50 Mhz, the notches are only 30 dB deep. Figure 3 shows the strength of rotation harmonics detected by a stripline monitor in the X-ray ring before and after passing through the correlator filter in the range 0-1500 Mhz. The reduced notch depth below 50 MHz is masked by the stripline response.

The Daresbury filter used 7/8" foam dielectric coaxial line made by Kabelmetal. In the range 250-750 MHz, the SRS filter has no notches less than 50 dB deep. the notch spacing errors are less than 9 KHz. The insertion loss midway between notches varies from 3 dB at 250 MHz to 6 dB at 750 MHz. The 750 MHz notch depth is 70 dB, as shown in Figure 4.

The length of RG-58C cable required for best performance should be about 10% of the length (in nanoseconds) of the 7/8" line. The exact length must be determined by measurement of notch depths. Substitution of an apparently identical splitter or perhaps use of RG-58 cable from a different manufacturer will require a readjustment of cable lengths. Clearly the most sensitive measure of performance is the depth and spacing of notches in the assembled filter. Figure 5 shows the change in depth of the 199.211 MHz notch of the X-ray filter as a result of interchanging the outputs of the H-81-4 splitter. The change in notch depth from 35 dB to 60 dB implies an asymmetry of .15 dB at this frequency.

To a good approximation, a correlator filter has input and output impedances of 50 ohms. This means that its performance is not affected by the impedance of the signal source to which it is connected. Figure 6 shows the result of cascading the X-ray ring filter with the filter built for the NSLS booster. The harmonic number of the booster is 5 and that of the X-ray ring is 30; so every sixth notch in the larger filter coincides with a notch of the smaller one. This figure shows the depth of the notch located at twice the RF frequency is about 100 dB.

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Feedback

The purpose of the SRS and NSLS correlator filters is to attenuate the rotation harmonic signals enough to allow distortionless amplification of betatron signals from the beam. This is achieved over a bandwidth ample for multibunch feedback without introducing undesirable phase shifts in the signal, which might lead to antidamping of some multibunch oscillation modes. Indeed, if the notches are deep enough, and the betatron phase advance from beam monitor to kicker is is proper, the output of the filter can simply be amplified linearly and applied to the beam to make a multibunch betatron damper. Such a damper has been operated in the NSLS booster [4]. To control a current-limiting instability, however, the damper must have loop gain higher than 100 dB, so further attenuation of the rotation harmonics is necessary. This was the case for the SRS and NSLS X-ray feedback dampers. The correlators were used as the first filter in narrow-band betatron damping circuits for the storage rings.

The Daresbury damping circuit has been used to counteract a horizontal instability that limited the current at 600 MeV injection energy and during acceleration. The instability was present only when the SRS was operated with one bunch filled. A signal from a stripline beam position monitor was used as input to the correlator filter. The output was then passed through a low noise broadband RF amplifier. Next, all beam signals excepting the betatron sidebands of the 500 MHz rotation harmonic were rejected by a single-conversion heterodyne receiver using a 500 MHz signal from the RF system as the local oscillator. The down-converted beam signal was passed through two reactive third-order elliptic lowpass filters, with nulls positioned to reject the nearest two rotation harmonics. After down-conversion and filtering, the betatron signal had a frequency varying from 500 KHz to 750 KHz during the acceleration cycle. The final component in the receiver is an operational amplifier. The receiver output was connected to a 100 watt, 10 MHz bandwidth amplifier, which excited an electrostatic kicker. The proper phase advance for damping was obtained by adjusting the phase of the local oscillator. Use of the damping circuit has made it possible to reduce the ring octupoles to zero without changing the instability threshold. At best, the damping circuit has been used to increase stored beam current by 25% during operation of the SRS with one bunch.

The damping circuit for the NSLS X-ray ring was designed to control a coupled-bunch vertical instability, dipole mode number 29. As at Daresbury, the input to the correlator filter was a beam position signal from a stripline. The correlator output was amplified and then processed through a two-path filter, a modified version of the longitudinal damper electronics in use at NSLS and designed by F. Pedersen [5]. The effect of the two-path filter is to amplify a betatron signal and phase shift it by some angle θ (or $-\theta$) if it is an upper(or lower) sideband. This filter consists of two single conversion heterodyne receivers. For this application the local oscillator was tuned to the 59th rotation harmonic (104 MHz) and was phase-locked to the RF. The filtering of the down-converted 0.350 MHz betatron signal consisted of three active third-order elliptic filters; one, a highpass filter, had its null response near the synchrotron frequency, 4 KHz; the other two were lowpass filters, one with its null at the rotation frequency(1.76 MHz) and the other having a null at 1.41(=1.76-0.35) MHz to prevent antidamping of mode numbers 28 and 0. The betatron signal was phase-shifted and used to amplitude-modulate a 104 MHz carrier derived from the local oscillator. The output of the two-path filter was applied to a pair of ENI 5100L amplifiers driving stripline kickers in the storage ring. The system was used to control the betatron instability during machine physics studies; after further development it will be used during operations.

Conclusions, Future Plans

Initial interest in correlator filters was aroused by their potential for use in stochastic cooling, with signal frequencies above 1 GHz. The two examples described here demonstrate that these filters are useful in applications with bunched beams. Notch depths of 50-65 dB can be obtained, over a bandwidth of up to 500 MHz. In practice, however, attenuation of unwanted beam signals may be as little as 45 dB at low frequencies because of variation in notch center frequencies due to asymmetry in the outputs of the 180° splitter, and the mismatch in dispersion between transmission lines. Notch depths greater than 65 dB in a single filter are attainable; however, merely flexing the RG-58C cable will degrade the notch depth at the 70 dB level. Thermal stability of the 7/8" cable is not a problem; for Andrew LDF-5-50, the thermal coefficient of the fractional change in electrical length goes from -9 parts per million per °C to +9 ppm/(°C) as the temperature changes from -30°C to 40°C,and approaches 0 at room temperature. One can reasonably expect to attain 45-50 dB rejection of rotation harmonics over the range 50-250 MHz, and better than 50 dB rejection in the range 250-750 MHz.

Plans for further development of correlator filters and betatron dampers at SRS will address any current-dependent phenomena observed after conversion to the High Brightness Lattice. Commissioning of the new lattice has begun. The NSLS X-ray ring will be shut down for installation of Phase II hardware [6], so development will continue on the NSLS VUV ring, using two cascaded correlators.

Acknowledgements

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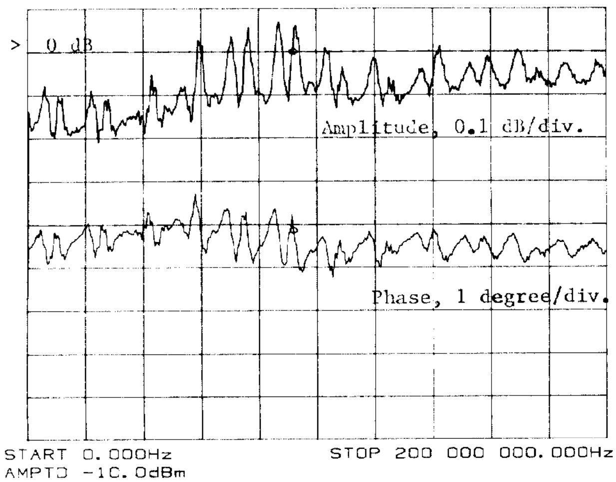

Figure 1. Comparison of 628 nsec LDF-5-50 to 61 nsec RG-58. Phase is referred to a 567 nsec ideal delay.

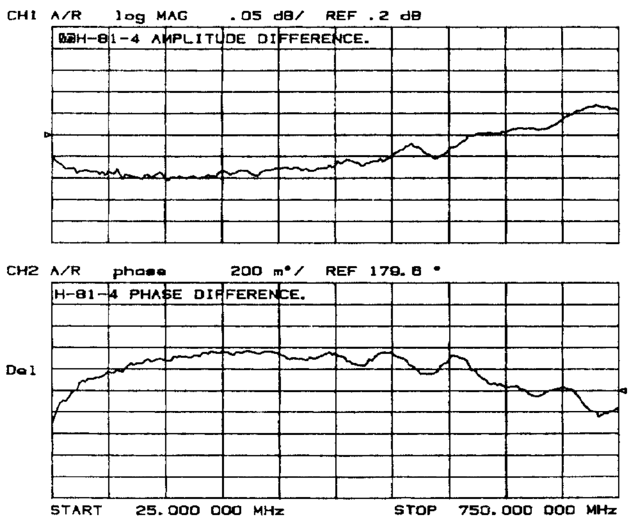

Figure 2. Amplitude and phase asymmetry of Anzac H-81-4 splitter.

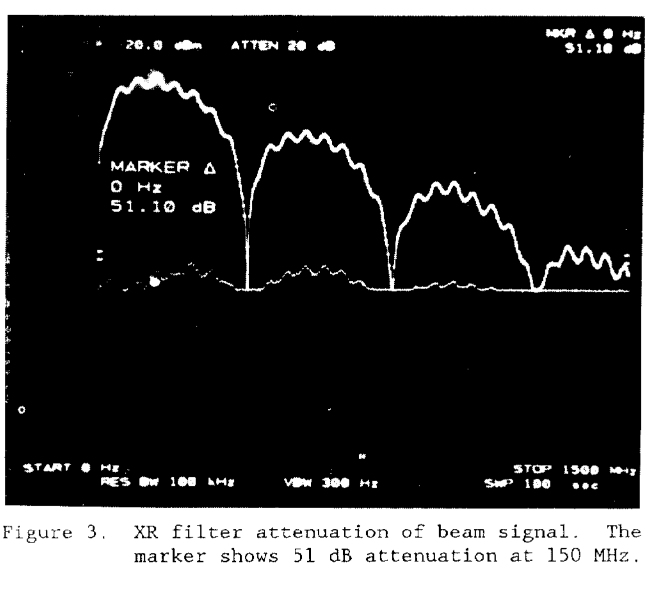

Figure 3. XR filter attenuation of beam signal. The marker shows 51 dB attenuation at 150 MHz.

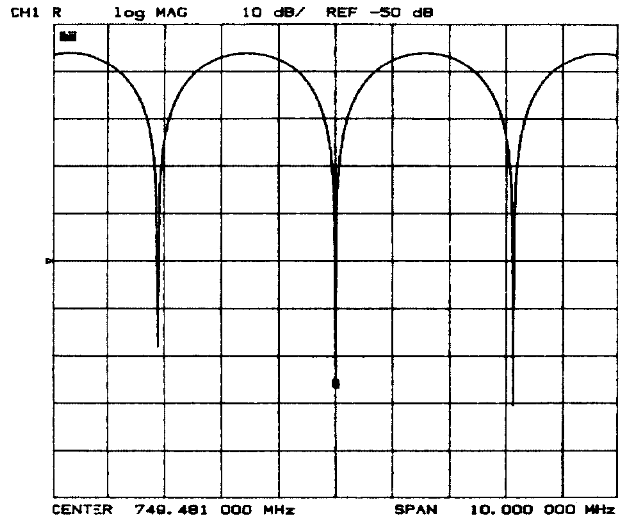

Figure 4. Daresbury SRS correlator 750 MHz notch. The notch depth is 70 dB.

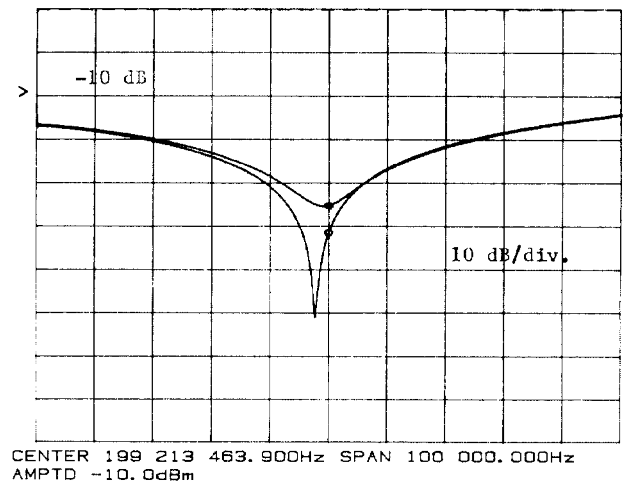

Figure 5. Effect of reversing H-81-4 on 199.211 MHz notch on the XR Correlator.

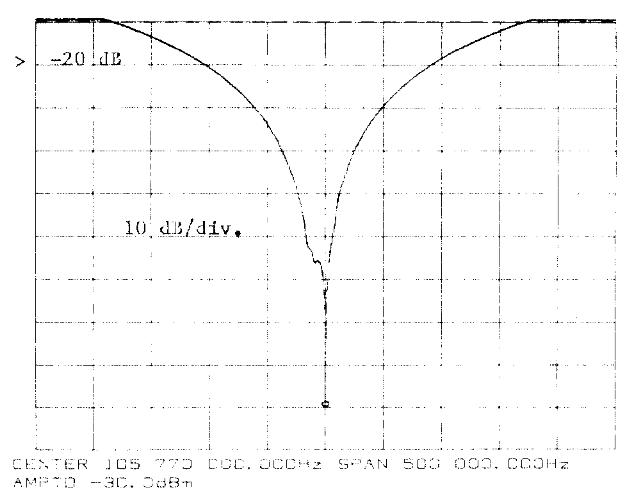

Figure 6. Cascaded NSLS booster and X-ray filters, 105.776 MHz notch. The input signal is -30 dBm; the notch depth is 100 dB.