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SUPERCONDUCTING DELAY LINE FOR STOCHASTIC COOLING FILTERS

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Introduction

The stochastic cooling system of the antiproton source at Fermilab uses notch filters for reducing the feedback power at frequencies corresponding to particles in the core. At the same time these filters assist in shaping the gain vs. momentum in the stack tail. These filters, therefore, must attenuate all the harmonics of the revolution frequency (629 kHz) in the operating frequency band (1 to 2 GHz). They require components providing delays of 1.59 μsec, with a minimum of attenuation and undesirable distortion in this passband. Transmission lines providing such delays are typically 328 m long (or 164 m if used in a reflecting mode), have a rather large diameter, and are fabricated from a high conductivity material to keep the attenuation sufficiently low. The use of superconductors allows a dramatic reduction in the diameter, total size and cost of this component in spite of the added cryogenic requirements.

Superconducting coaxial transmission lines are not new. N.S. Nahman[1] concisely traced their development from his invention in 1960 to 1973. Y. Hoshiko[2] and H. Yoshikiyo et al[3] described the development of such cables in Japan. While pursuing ways of manufacturing or procuring such transmission lines, we measured the performance of two such cables in order to demonstrate the feasibility of the superconducting cable notch filters concept.

Description of Delay Lines

The first cable is a 84 m long piece of a superconducting coax which to the best of our knowledge agrees with the one described by A.J. Cummings and H. Kuettner.[4] We sinked this cable slightly by drawing it through a 1.57 mm diameter die and wrapped it with mylar tape. This coaxial cable consists of a solid Niobium inner conductor of .37 mm diameter, inside a teflon dielectric of 1.17 mm diameter, a .22 mm thick lead outer conductor and an outer jacket of 25 μm thick mylar tape 6.35 mm wide wrapping with 50% overlay. The aluminum spool containing this cable is 40.6 cm long, has a core diameter of 10.2 cm and fits in a He vapor shielded dewar 117.0 cm tall with 46.0 cm diameter. Helium requirements for the dewar are approximately one 25 ℓ transfer every 40 hours.

The second cable made available to Fermilab by KEK, was manufactured by Furukawa and has been described in references 2 and 3. It is a 1.0 km long coaxial line with an inner conductor of lead plated copper wire of .48 ±.001 mm diameter, a FEP teflon dielectric of 1.57 ±.002 mm diameter and an outer conductor of lead plated copper tape with inner diameter of 1.60 ±.005 mm. The outer conductor has a longitudinal seam and is wrapped with a mylar tape with 50% overlay. The lead platted layer is 3 μm thick.

*Operated by Universities Research Association Inc., under contract with the U.S. Department of Energy.

Description of Filters

One of the simplest notch filter would use this cable as the shorted delay line in figure 1.

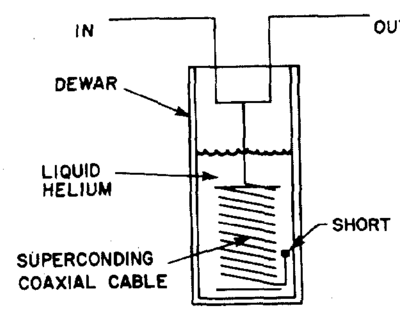

Fig. 1 Shorted delay line filter

This type of filter is particularly sensitive to the uniformity of the line. Irregularities are sources of reflections that remain practically unattenuated due to the superconducting nature of the cable. The result of these unattenuated multiple reflections is a filter with notches that are irregular both in attenuation depth and frequency spacing. A computer simulation of a shorted cable with characteristic impedance variations randomly distributed in positions and amplitude yielded such a result, leading us to the above explanation as well as to estimates on the dimensional tolerances needed for the required notch pattern uniformity. The result of this program for frequencies around 1 GHz can be expressed as

$$\frac{\Delta f}{N f_o} = 2.8 \times 10^{-4} \sqrt{n} \ \frac{\Delta Z}{Z_o}$$

where n = number of discontinuities, f_o = frequency interval between notches and $\Delta Z/Z_o$ = relative rms impedance variation. Thus, for notch dispersion of $\Delta f/Nf_o = 10^{-5}$ in a line made up by discontinuities of average length $\lambda/2$, the rms impedance variation ΔZ should be $\pm.06\Omega$ for a cable with $Z_o = 50\Omega$. This requires dimensional tolerances on the order of ±.1%.

Multiple reflection due to irregularities are much less important in the performance of a correlator-type filter[5] since no use is made of the reflected wave. Figure 2 shows its schematic. A computer simulation similar to the one above for a correlator filter yields

$$\frac{\Delta f}{N f_o} = 2.6 \times 10^{-5} \ n^{.75} \left(\frac{\Delta Z}{Z_o}\right)^2$$

indicating that for the same dispersion the tolerances can be larger by one order of magnitude.

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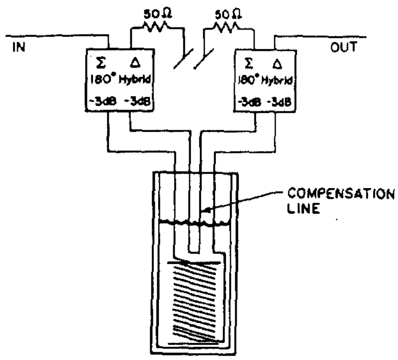

Fig. 2 Correlator filter

Measurements

We report here the performance of these cables in filters as measured with a HP8409C Auto Network Analyzer in the range 1 to 2 GHz. Higher frequencies ranges were also studied but in a less systematic way. The network analyzer has a phase lock subsystem which allows a frequency resolution better than 100 Hz. The sharp notch bottoms were measured with a precision of 100 Hz and the rounded peaks between them with a precision of 500 Hz. In order to reduce the number of data points to be handled, five consecutive notches are individually measured, their data averaged and recorded as a function of the frequency (of the first notch) for further processing. We have satisfied ourselves that this averaging does not affect the general character of the results.

Besides the attenuation of the notches, the other important characteristic of these filters is the uniformity of the frequency interval between notches. Ideally the frequency of a notch is a harmonic of f_o. In order to plot the deviation from this behaviour all notch frequencies are measured, the average value of the intervals between them is calculated and taken to be f_o. The harmonic order of the notch at frequency f is then $n = [f/f_o]$, where the square bracket denotes closest integer. The relative deviation $\delta = (f-nf)_o/nf_o$ is then calculated for all notches and their average, $\bar{\delta}$, used for the plotting of an adjusted deviation: $\delta - \bar{\delta}$. This adjusted deviation in parts per million (ppm) is finally plotted versus f and loosely labelled as a Relative Notch Interval Variation.

The 84m cable in a shorted delay line filter presented unacceptably high variations in the frequency interval between notches. In a correlator-type filter, however, they are more reasonable and the data is presented in Figure 3, with attenuation of the notches shown in the upper graph. The value of f_o for this filter is 2.44 MHz. The scales of the graphs were selected for stressing details instead of facilitating comparisons between filters.

Figure 4 presents the corresponding data for the 1 km cable, again used in a correlator-type filter. We notice that the notches are deeper specially near 1.5 GHz, and the adjusted deviation much smaller than with the 84m cable. The linear dependence on frequency is due to a slight phase mismatch in the hybrids. This rather smooth line indicates an adjusted deviation of less than 1 ppm. The value of f_o was 210.80 kHz and n varied from 4762 to 9524.

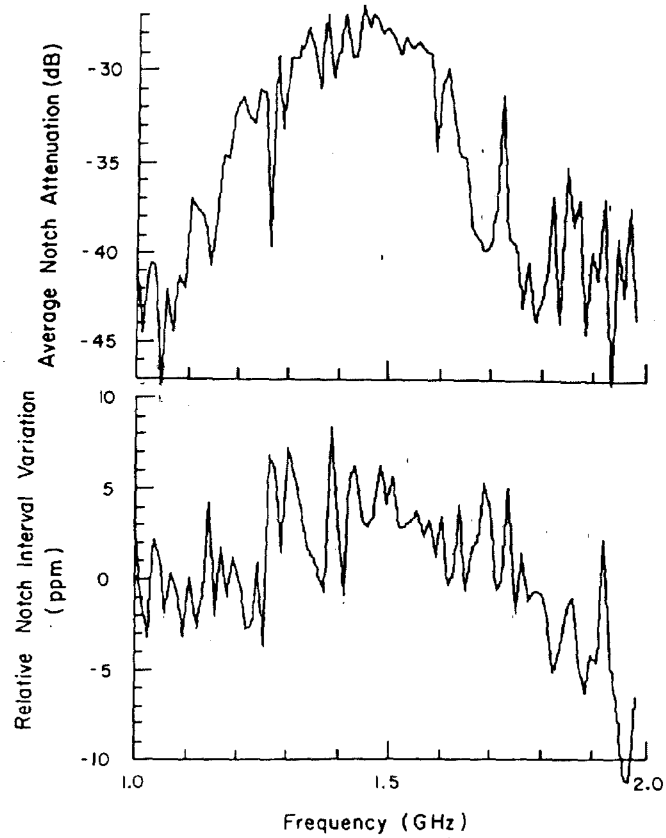

Fig. 3 Data from 84m cable in correlator filter

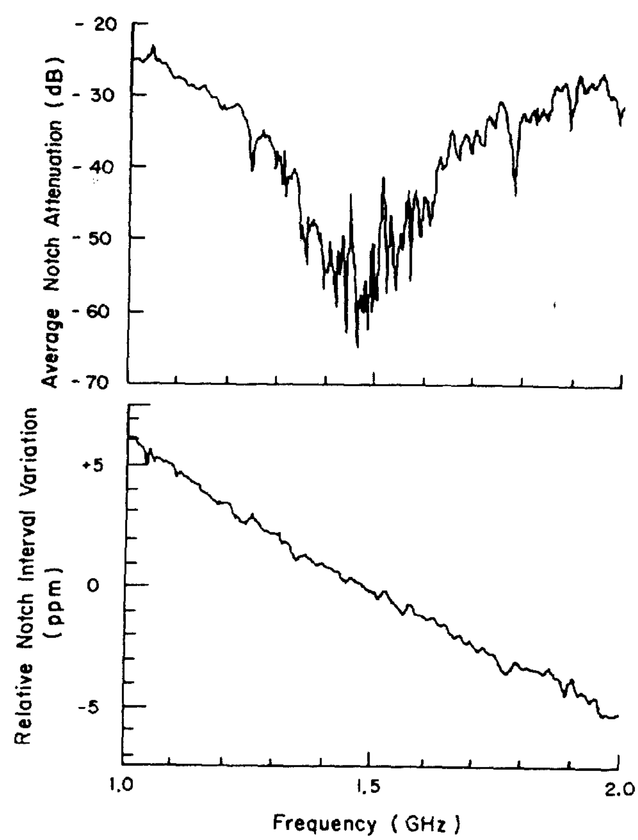

Fig. 4 Data from 1km cable in correlator filter

When this 1 km cable is used as a shorted delay line filter, f_o = 105.35 kHz and a systematic measurement of all notches ($9492 < n < 18984$ becomes impractical and we therefore restricted it to 3 partial bands as shown in Figure 5. The positive slope of the attenuation is due to the increased dielectric losses of the cable as function of frequency.

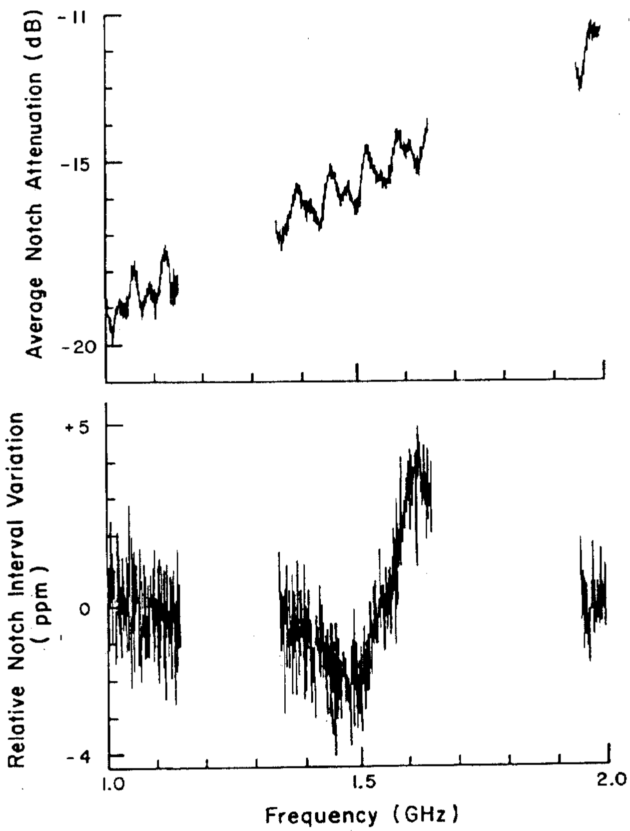

Fig. 5 Data from 1km cable in shorted delay line type filter

Conclusion

The above measurements indicate that the notch depths and frequency dispersion of these filters are within the acceptable design limits for the Fermilab antiproton source. We are proceeding to measure their stability with regard to the liquid He level and their capability for handling high power signals for possible use after the amplifiers. The manufacture of a prototype filter with the proper f_o (629 kHz) is also under way.

It is a pleasure to acknowledge the technical work of W. Mueller and the contribution of B. Hyslop.

References

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