PBAR NOTE 586
TRANSMISSION OF STOCHASTIC COOLING SIGNALS IN THE RECYCLER RING USING TE_{01} CIRCULAR WAVEGUIDE

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INTRODUCTION

The stochastic cooling systems in the Recycler Ring have a bandwidth on the order of 1 GHz. The length of the transmission link between pickup and kicker of the cooling systems is on the order of 1 km. This long length prohibits the use of coaxial transmission lines.

Using TE_{01} Circular Waveguide is an old and well-established technique[1] for transmitting microwave communication signals over long lengths with low loss. This paper will give a simple design using TE_{01} Circular Waveguide in the Recycler. Using this type of waveguide with a diameter of 3.6", a 1 GHz bandwidth signal at a carrier frequency of 20 GHz would suffer an attenuation of 0.7dB/km. A straightforward equalizer design would limit the phase distortion to less than 10 degrees.

THE TE_{01} CIRCULAR WAVEGUIDE MODE

In a cylindrical coordinate system (z = longitudinal, ρ = radial, ϕ = azimuthal), the fields in a TE_{0n} circular waveguide are:

$$H_z = H_o J_0\left(\frac{\omega_c}{c}\rho\right) \tag{1}$$

$$H_\rho = j\sqrt{\left(\frac{\omega}{\omega_c}\right)^2 - 1}\cdot H_o J_1\left(\frac{\omega_c}{c}\rho\right) \tag{2}$$

$$E_\phi = j\frac{\omega}{\omega_c}\eta H_o J_1\left(\frac{\omega_c}{c}\rho\right) \tag{3}$$

where J_0, J_1 are Bessel functions, c is the velocity of light, η is the impedance of free space, and ω_c is the cutoff frequency of the waveguide:

$$\omega_c = \frac{c}{a}\tau'_{0n} \tag{4}$$

where τ'_{0n} are the zeros of the J_1 Bessel function and **a** is the radius of the waveguide.

Since the current flowing on the waveguide walls is given by $\vec{J}_s = \vec{H}\times\hat{n}$, there is no longitudinal current flowing in the waveguide. The only current is azimuthal and is independent of frequency. Therefore the attenuation in the waveguide due to the

[1] "Waveguide as a Communication Medium", S.E. Miller, The Bell System Technical Journal, Vol. 33, No. 6, November 1954, pp 1209-1265

resistivity of the waveguide walls will decrease dramatically with frequency. The attenuation in dB per length is:

$$\frac{dB}{L} = 8.6858 \frac{1}{a} \frac{\omega_c}{\sqrt{\omega^2 - \omega_c{}^2}} \frac{R_s}{\eta} \tag{5}$$

where:

$$R_s = \sqrt{\frac{\omega\mu}{2\sigma}} \tag{6}$$

μ is the permeability of free space and σ is the conductance of the waveguide walls.

The phase and group velocity of a wave travelling in a waveguide is not the same for all frequencies. The error in phase for a signal that has traveled a distance L with a frequency of $\Delta\omega$ away from the center frequency ω_0 of the system is:

$$\Delta\theta = \omega_0 \frac{L}{c} \left(\sqrt{\left(\frac{\Delta\omega}{\omega_0} + 1\right)^2 - \left(\frac{\omega_c}{\omega_0}\right)^2} - \frac{\frac{\Delta\omega}{\omega_0} + 1}{\sqrt{1 - \left(\frac{\omega_c}{\omega_0}\right)^2}} \right) \tag{7}$$

To make the phase equalizer design straightforward, it is desirable to keep the phase excursion given by Equation 7 to be less than 360 degrees. For an operating frequency range of 1 to 2 GHz, this would require a cutoff frequency of around 75 MHz. A cutoff frequency of 75 MHz would require a huge waveguide diameter that would be impractical.

SINGLE SIDEBAND AM MODULATION

The large waveguide dispersion could be avoided if the stochastic cooling signal is up-converted to a higher frequency, transmitted through the waveguide, and then down-converted to the original frequency range. A block diagram of this frequency conversion scheme is shown in Figure 1. The scheme in Figure 1 uses a single sideband AM modulation to minimize the bandwidth, hence the dispersion of the transmission. Because of the single sideband scheme, the local oscillator signal must be fed through the waveguide as well. Actually the half frequency of the local oscillator is transmitted. This minimizes the need for vary sharp filters to separate the local oscillator signal and the signal band at the down convert side. Since the local oscillator frequency is at a single frequency and contains no cooling information, this signal could be shipped to the down-convert side by other means such as optical fiber.

A waveguide with a 3.6” diameter has a cutoff frequency of 4 GHz for the TE_{01} mode. If the local oscillator frequency is 20 GHz, the loss of signal is 0.7 dB/km for copper walls and 0.85 dB/km for aluminum walls. The dispersion of the signal after down-conversion over a frequency range from 1-2 GHz for a transmission length of 1 km is shown in Figure 2.

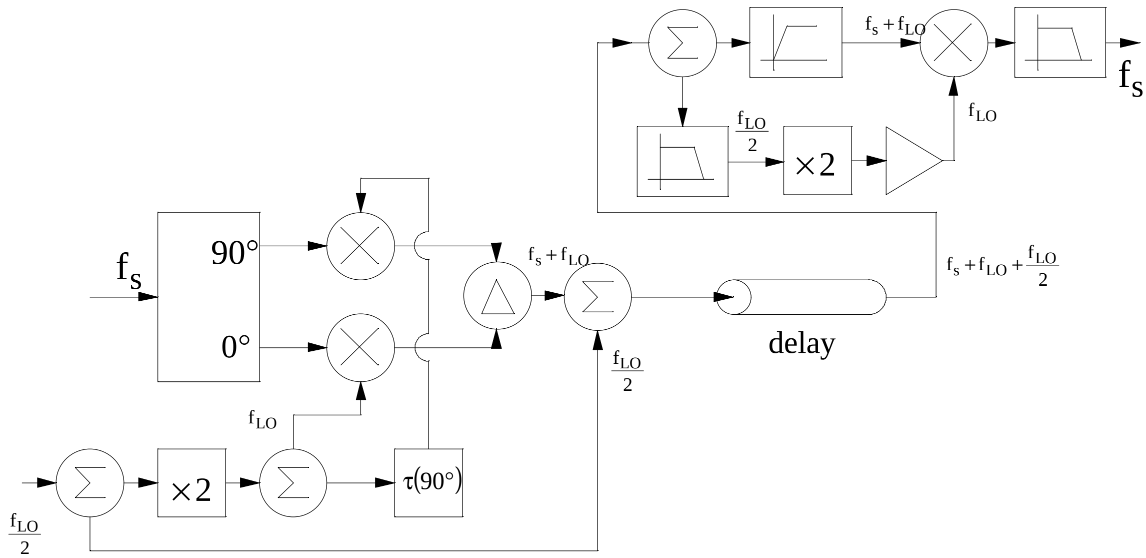

Figure 1. A sketch of the frequency up and down conversion scheme.

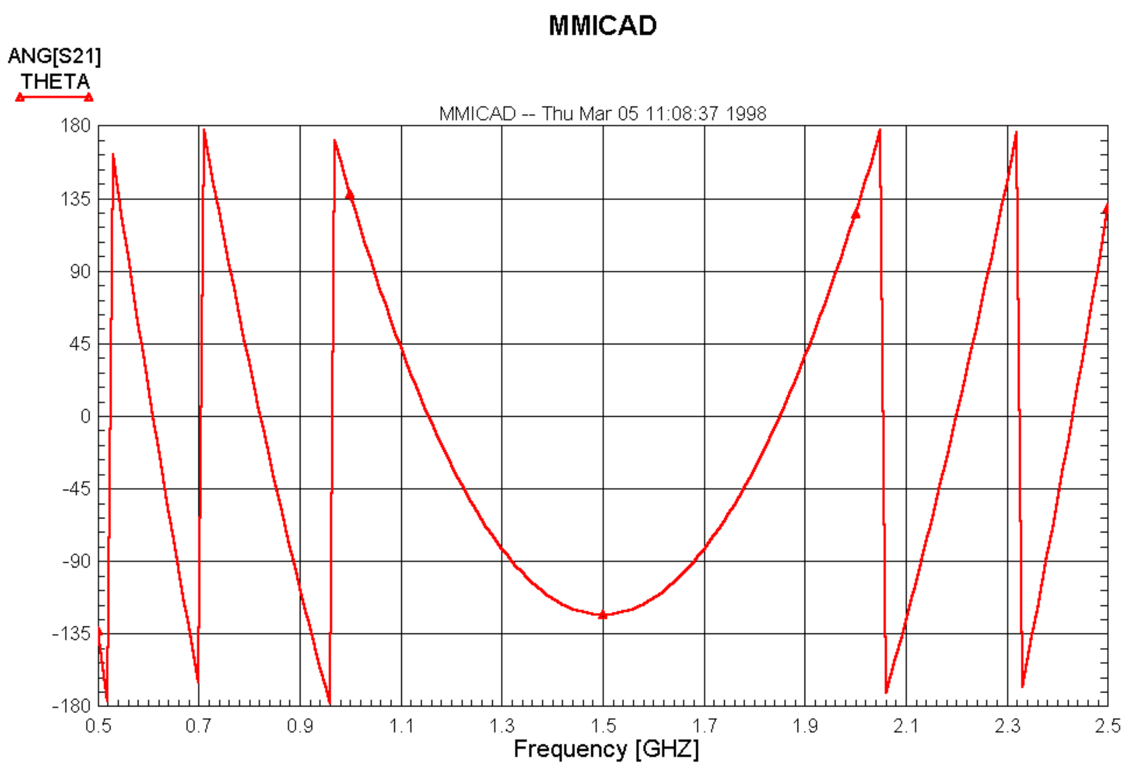

Figure 2. The dispersion of the cooling signal after it has been transmitted 1 km.

The Phase Equalizer

Although the phase excursion shown in Figure 2 is on the order of 360 degrees, building a phase equalizer should be straightforward. One method for building a phase equalizer is to use a Finite Impulse Response (FIR) filter (these filters are also known as transversal filters or chirp filters) At microwave frequencies these filters are constructed from coupled transmission line sections as shown in Figure 3. A simple 24-tap filter was designed to remove the phase excursions from 1-2GHz as shown in Figure 2. The filter coefficients are listed in Table 1.

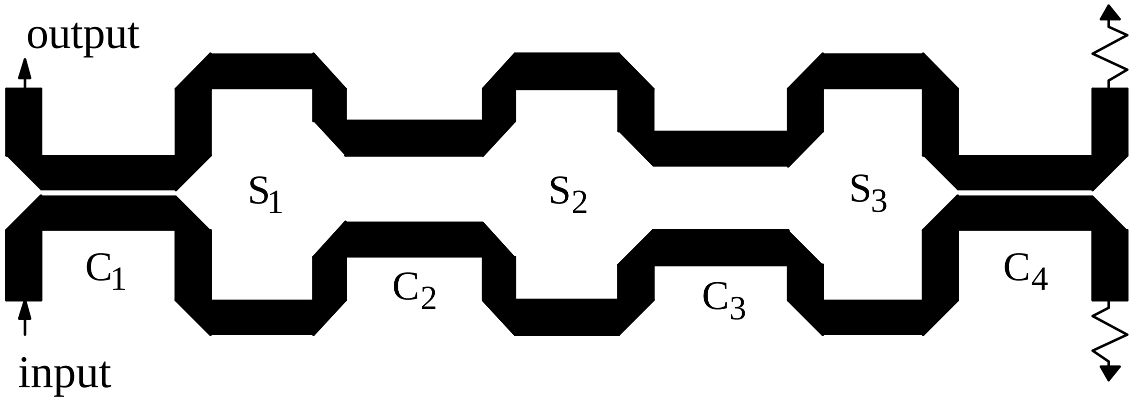

Figure 3. An microstrip layout of a FIR Filter. Each coupling section has a coupling amplitude, C_n, a coupling length, L_n, and a spacing length, S_n.

Section	Coupling Amplitude (dB)	Coupling Length (ps)	Spacing Length (ps)	Section	Coupling Amplitude (dB)	Coupling Length (ps)	Spacing Length (ps)
1	-195.7	254	254	13	-26.9	133	133
2	-226.8	275	275	14	-25.8	117	117
3	-44.1	280	280	15	-29.5	119	119
4	-32.7	271	271	16	-34.1	133	133
5	-23.1	250	250	17	-34.3	119	119
6	-20.1	229	227	18	-33.6	101	98
7	-20.0	204	203	19	-37.4	113	107
8	-21.1	176	177	20	-41.4	141	118
9	-23.5	165	166	21	-41.4	102	98
10	-20.8	149	150	22	-46.0	164	181
11	-23.7	141	139	23	-72.4	139	149
12	-23.4	134	132	24	-49.2	109	161

Table 1. Filter Coefficients for a 24 tap phase equalizer. The insertion loss of this filter is about 10 dB.

The amplitude response of this filter is shown in Figure 4. The insertion loss of the filter is about 10 dB. The phase response of the filter is shown in Figure 5. Figure 5 shows that the phase excursion can be reduced to ±10 degrees.

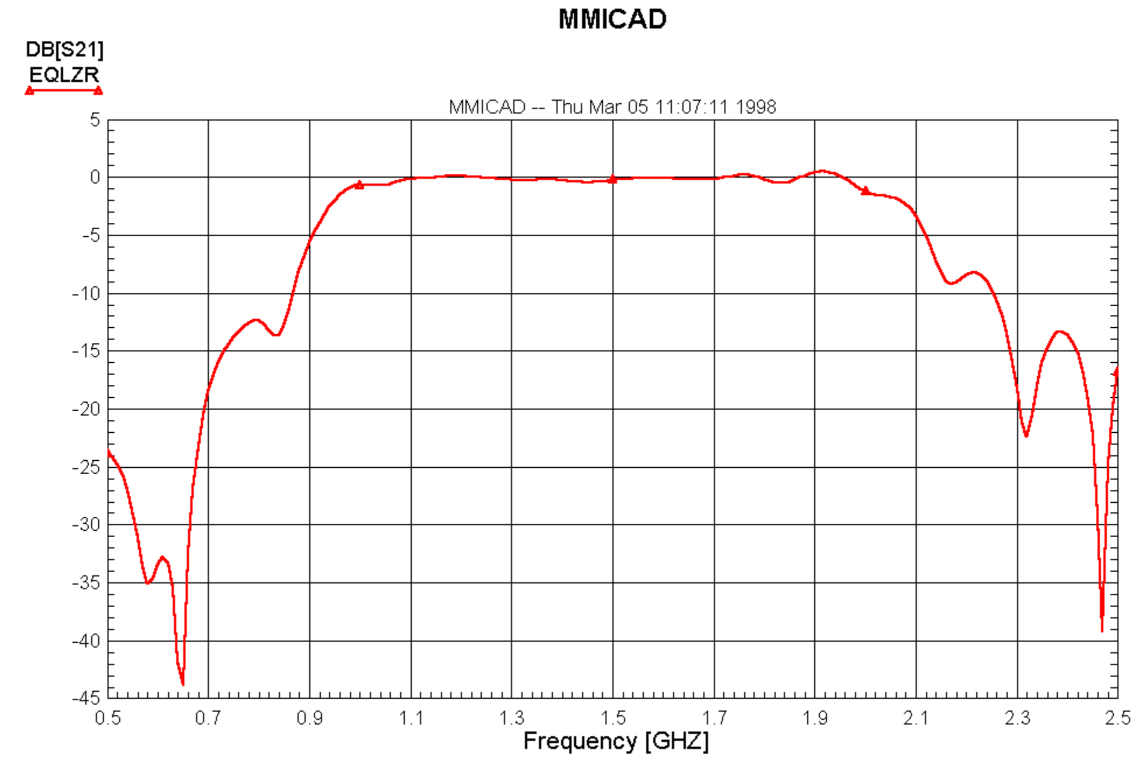

Figure 4. The amplitude response of the 24 tap phase equalizer. The insertion loss of the filter is about 10 dB

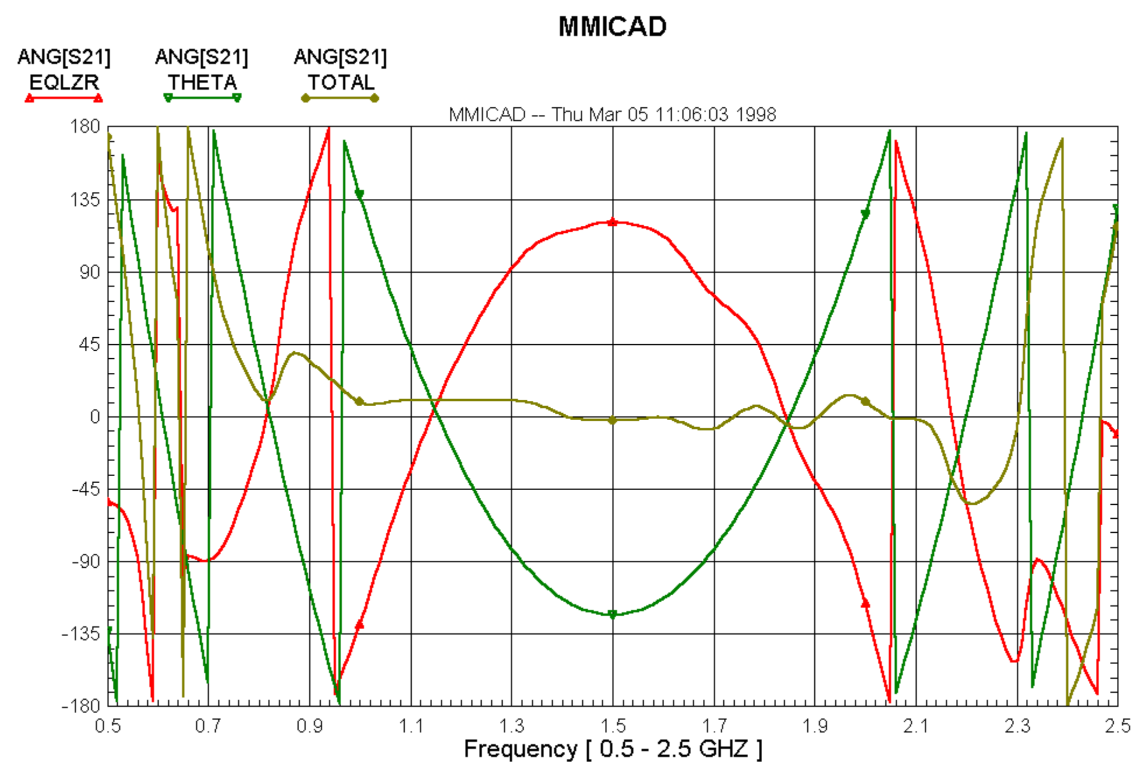

Figure 5. The phase response of the equalizer.

THE TE_{01} COUPLERS

Probably the most difficult part of the transmission system is the mode launchers that would take a coaxial field pattern and convert it to a TE_{01} circular waveguide field pattern. Figure 6 shows a sketch of the mode conversion from rectangular TE_{10} waveguide to cylindrical TE_{01} waveguide. (The mode launch from a coaxial transmission line to rectangular TE_{10} waveguide is straightforward.) With a 3.6" diameter waveguide at 20 GHz, there will be over 40 modes that can propagate in the waveguide. Most of these modes have large attenuation factors (>20dB/km) so if the mode launcher inadvertently converts some of the signal into these unwanted modes, it will simply appear as signal loss. However, the above cutoff TE_{0n} cylindrical modes (modes $1<n<6$ can propagate) will have low attenuation factors. Conversion to these modes could result in signal distortion because of the difference in phase velocity between these different modes. Therefore, the mode launcher must be designed carefully so as not to couple to the above cutoff TE_{0n} cylindrical modes.

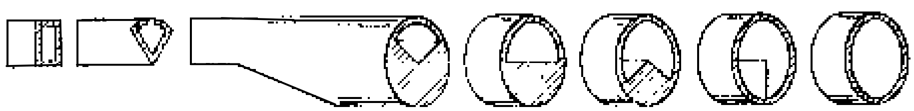

Figure 6. Sketch of a mode coupler between the rectangular TE10 waveguide to the cylindrical[1]

MODE CONVERSION

A similar problem to the mode launchers is the problem of mode conversion due to imperfections in the walls of the waveguides. The most serious problem would be conversion into an unwanted mode and then re-conversion into the TE_{01} mode. Because of the different group velocities between the modes this would look like phase distortion. For the modes that are well above cutoff, the group and phase velocities approach the speed of light, which minimizes the problem somewhat. The level of mode conversion that can be tolerated would put a specification on the quality of the waveguide walls. Also, if the imperfections do not change over time, the phase distortion could be accounted for in the phase equalizer that was discussed earlier. Another way to minimize the effect of mode conversion would be to periodically place mode filters in the waveguide that removed unwanted modes but passed the desired TE_{01} mode.

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[2] "Waveguide as a Communication Medium", S.E. Miller, The Bell System Technical Journal, Vol. 33, No. 6, November 1954, pg 1254