LOADED DELAY LINES FOR FUTURE R.F. PULSE COMPRESSION SYSTEMS[†]

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Abstract

The peak power delivered by the klystrons in the NLCTA (Next Linear Collider Test Accelerator) now under construction at SLAC is enhanced by a factor of four in a SLED-II type of R.F. pulse compression system (pulse width compression ratio of six). To achieve the desired output pulse duration of 250 ns, a delay line constructed from a 36 m length of circular waveguide is used. Future colliders, however, will require even higher peak power and larger compression factors, which favors a more efficient binary pulse compression approach. Binary pulse compression, however, requires a line whose delay time is approximately proportional to the compression factor. To reduce the length of these lines to manageable proportions, periodically loaded delay lines are being analyzed using a generalized scattering matrix approach. One issue under study is the possibility of propagating two TE_{on} modes, one with a high group velocity and one with a group velocity of the order 0.05c, for use in a single-line binary pulse compression system. Particular attention is paid to time domain pulse degradation and to Ohmic losses.

I. INTRODUCTION & METHODOLOGY EMPLOYED

Electron-positron colliders in the TeV range will require microwave sources delivering power in the hundred megawatt range. The large power demands are alleviated to some extent through the use of pulse compression techniques in which the power of the pulse is enhanced at the expense of the time duration of the pulse.

In order to reduce the length of the delay lines necessary to store the energy for a pulse compression scheme the characteristics of a delay line periodically loaded with thick irises are investigated. In the SLED-II[1] system (SLAC energy development system using resonant lines), overmoded circular waveguides are used to store energy from the early portion of the output pulse from the klystrons. Once the line is charged the phase of the klystron is reversed, leading to a discharge of this energy at a reduced pulse width and enhanced overall pulsed power. To achieve a pulse of length 250 ns requires a delay line of length 36 m.

The length of the line can be reduced by loading it periodically with irises, in order to reduce the group velocity of the wave. In BPC (binary pulse compression[2]), in which the peak power is doubled in successive stages. At each stage it is required to delay the progress of the wave from the first half of the pulse with respect to the last half, so that they arrive synchronously in time at the output of the stage. To achieve this end, either two lines are required, one with a low group velocity and one with a group velocity near c, or a delay line propagating two different modes simultaneously with widely differing group velocities. We explore this latter method with a TE_{01} mode and a TE_{02} mode propagating in a delay line consisting of a large number of inward and outward steps (thick irises)

The theoretical gain of a BPC system is 100% for a system consisting of components with infinite conductivity in which no mode conversion occurs at discontinuities. However, in reality the system possesses finite Ohmic wall losses which both degrade the shape of the pulse and reduce the overall system efficiency and finite mismatches occur at waveguide discontinuities. Ohmic wall losses are paid attention to by allowing the axial wavenumber to possess both a real and imaginary component (the latter corrersponding to the wall losses) and also, by taking into account transverse wall losses in a multi-mode S-matrix analysis.

Our initial investigation in the area of multi-mode propagation down iris-loaded delay lines revealed that the highest order propagating mode can undergo significant reflection under resonance conditions (this is a choke mode), and that the mode below in frequency can also be delayed as a consequence of the avoided crossing in the characteristic dispersion curves of the waveguide. However, it is not possible to operate in a choke mode regime for lower order propagating modes. For this reason we chose the diameter of the waveguide to be 2.32 inches (the cut-off of the TE_{02} mode lies at 11.36GHz) and the outward radial step (negative iris) is chosen to be three times larger. The choice of the latter diameter dictates the group velocity and the point of avoided crossing in the dispersion curves.

II. APPLICATION OF MODE MATCHING METHOD TO THE DISPERSION CHARACTERISTICS OF LOADED DELAY LINES

The Brillouin diagrams for the loaded delay lines are calculated using a scattering matrix method involving

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matching the electric and magnetic field at either side of the aperture region of a periodic structure. This mode matching method converges provided a sufficient number of modes is used to represent the field at transitions in the geometry of the waveguide.

Firstly, the *generalized* lossless S-Matrix of a single narrow to wide transition (NW) is calculated by matching the complete modally decomposed field at the transition:

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} 2q_0^{-1} - I & 2q_0^{-1} p_0 \\ a(S_{22} + I) & aS_{21} + I \end{pmatrix} \qquad (2.1)$$

where the q_0 and p_0 matrices are given in terms Y, the admittance matrix of the wide transition and $\hat{Z}$, the impedance matrix of the narrow transition:

$$q_0 = I + \hat{Z}a^t Ya, \; p_0 = \hat{Z}a^t Y \qquad (2.2)$$

The inner product matrix is given by:

$$a = \int_{S_{ap}} e.\hat{e} dS \qquad (2.3)$$

where the integral is performed over the aperture plane of the waveguide transition and the nomalised mode functions **e** and $\hat{\mathbf{e}}$ correspond to circular waveguide mode functions[3] of the wide section and the narrow section respectively. The NW matrix is cascaded with the wide to narrow (WN) transition to give the overall narrow to wide to narrow (NWN) scattering matrix for all modes (including evanescent modes). This matrix is converted into a multi-mode transmission or wave-amplitude matrix by applying the matrix relation:

$$\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \begin{pmatrix} S_{21}^{-1} & -S_{21}^{-1} S_{22} \\ S_{11} S_{21}^{-1} & S_{12} - S_{11} S_{21}^{-1} S_{22} \end{pmatrix} \qquad (2.4)$$

Finally, the eigenvalues of the multi-mode wave-amplitude matrix, for a given frequency, are of the form $\exp(j\Psi)$. Real values of Ψ correspond to modes within the pass-band of the Brillouin diagram. In practice twenty or more modes are necessary in order to adequately satisfy the boundary conditions. For a single waveguide mode propagating within the structure it is sufficient to consider a single mode wave-amplitude matrix (all modes are of course retained in the S-matrix calculation). However, for two propagating modes it is necessary to maintain the full-mode wave-amplitude matrix in the calculation of the eigenvalues.

Thus, the method proceeds with a search for real phase values as a function of frequency; the dispersion diagram is constructed by inverting the resulting phase dependence on frequency. Complex phase values of purely imaginary content are rejected as this represents waves within the stop-band region.

III. DISPERSION CHARACTERISTICS OF MULTIPLY LOADED DELAY LINES

The narrow and wide transition are .5 inches and .53 inches in length respectively. The latter dimension was chosen in order to allow at least one radial mode to propagate within the wide transition (i.e. the negative iris region). The radius of the narrow waveguide, viz, 1.16 inches, was chosen with a view to allowing two azimuthally symmetric TE modes to propagate in order to operate close to the cut-off of the upper band TE mode. The below fig. 1 shows the characteristic dispersion diagram for the chosen loaded delay line. The dashed line also indicated is the characteristic velocity of light line.

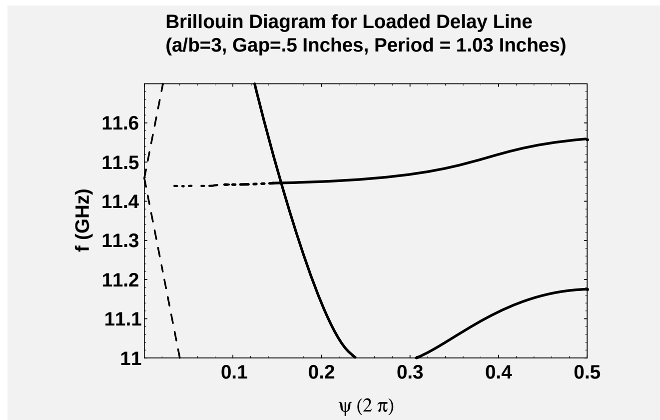

Figure 1: Brillouin Diagram for a Loaded Delay Line

The wide transition (i.e. the negative iris) has the effect of splitting the smooth wall dispersion curves. This avoided crossing in the dispersion curves allows one to have two waves propaging down the periodic structure. At a frequency of 11.503 GHz there is simultaneously a high group velocity wave of -0.7c (i.e. a backward wave) and low group velocity wave of 0.05c. This allows for the possibility of operating a binary pulse compression system in a a single loaded delay line.

IV. PULSE PROPAGATION THROUGH SLED DELAY LINES

The progress of the pulse through the structure is monitored by the convolution of the input signal with the time response of the loaded delay line. To model the propagation of a pulse through the SLED delay lines we require the frequency response function of the loaded waveguide. The inverse transform of the product of the response function and the Fourier spectrum of the pulse allows the progress of the pulse through the structure to be monitored. The response function is obtained by evaluating the overall scattering matrix of the structure.

The effect of Ohmic losses is an important consideration. Wall losses are paid attention to using wavenumbers in which Ohmic losses are taken into account utilizing third order perturbation in the exact eigenvalues (the first order perurbation method is invalid close to the cut-off region of the waveguide) and also by calculating the scattering matrix of each NW transition incorporating Ohmic losses due to the presence of the transverse wall. The generalized scattering matrix of a single transition is given by:

$$\begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} 2q^{-1} - I & 2q^{-1}p \\ d^{-1}a(S_{22} + I) & d^{-1}(aS_{21} - 2I) + I \end{pmatrix} \tag{4.1}$$

where:

$$\begin{aligned} &q = I + \hat{Z}a^{t}\overline{Y}a,\ p = \hat{Z}a^{t}\overline{Y},\ d = I + R_{m}w\overline{Y}, \\ &\overline{Y} = Yd^{-1},\ w = I - a\,a^{t} \end{aligned} \tag{4.2}$$

I is the unit matrix, a^t is the transpose of the matrix of inner products of the nomalised mode functions, and R_m represents the wall resistance of the waveguide. In the limit of infinte wall conductivity (4.1) becomes (2.1). This scattering matrix is cascaded with succeeding matrices to give the overall matrix of the structure in the frequency domain.

The input trapezoidal pulse with of duration 250 ns and a sharp rise and fall time of 5 ns, together with the amplitude of its Fourier spectrum are illustrated in the below fig. 2.

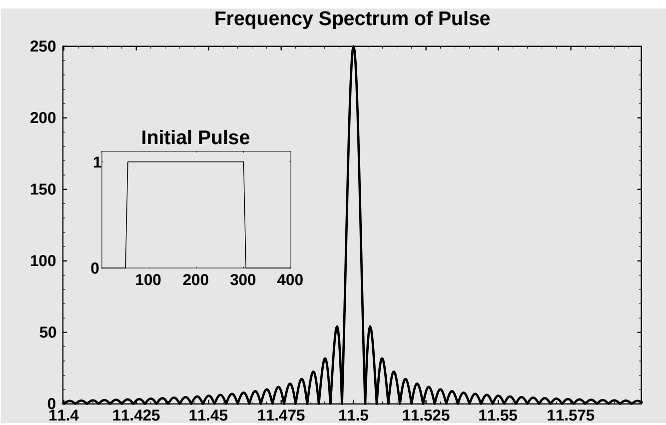

Figure 2: Input Waveform & Fourier Spectrum

Also shown in fig. 3 is the waveform corresponding to the propagation of a TE_{01} mode through one thousand and twenty four cells . The shape of the leading edge of the pulse is degraded by presence of the dispersive loaded delay line. However, even for this particularly large number of irises the overall shape of the pulse suffers remarkably little degradation. Ohmic wall lossses of the system are of course unavoidable and this accounts for the diminished amplitude and overall area of the transmitted pulse. The TE_{02} suffers substantially larger Ohmic wall losses and to reduce these losses for multi-mode propagation one must use superconducting waveguide.

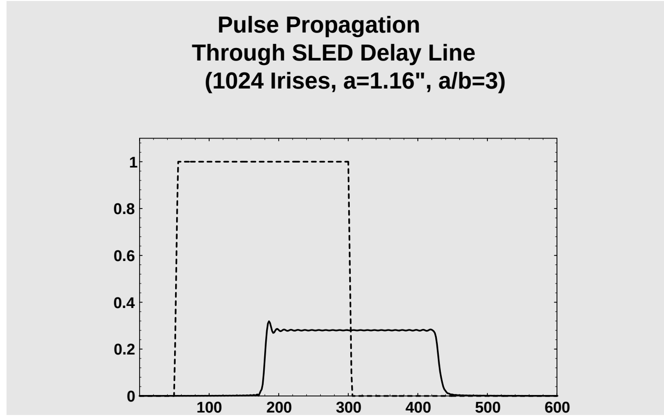

Figure 3: Pulse Propagation Through Loaded Delay Line

V. DISCUSSION

The concept of using a single-line iris-loaded waveguide to simultaneously delay the progress of two input pulses has been demonstrated, but the losses associated with the higher order mode (TE_{02} in this case) have been shown to be too high to be acceptable for practical purposes, unless one is prepared to utilize superconducting iris-loaded waveguide. However, a superconducting waveguide will impose a limit on the magnetic field that is tolerable and so limits the power transport through the system.

VI. REFERENCES

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