Overmoded Delay Line
and Component Tolerances

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Introduction

This work is ongoing. I present a progress report, rather than a conclusive study.

The goal is to get a handle on microwave functional requirements, and not to give hard engineering specifications.

- Delay Line Attenuation and Flange Gaps
- Parasitic Modes
- Analytic Mode Mixing Code for Tolerancing Waveguide
- Dangerous Resonances
- Discrete Discontinuities
- Components
Longer-pulse klystrons (3μs) allow us to go from previous four-feed design to an eight-feed system, cutting the number of klystrons in half.

The total amount of delay line, however, is doubled, and the average delay line distance traveled by rf is increased a factor of 2 1/3.
Delay Line Waveguide

To maintain transmission efficiency, the additional waveguide length is compensated by increasing the diameter from 4.75” to 6.725”.

Ohmic attenuation constants versus copper waveguide diameter for TE\(_{01}\) and TE\(_{12}\).

Average delay line ohmic loss efficiency factor for dual-moded TE\(_{01}/TE_{12}\) DLDS systems with compression ratios of four and eight versus delay line diameter.
Experiments performed jointly with KEK at ATF in 1999-2000.

Demonstrated efficient long distance (55m) transmission of TE01, TE12, and later TE02 through WC475.

Gave information about parasitic mode losses flange joint effects.
TE01(02) is immune to short gaps, due to strictly azimuthal wall currents. Longitudinal currents of TE_{12} couple it to flange gaps. Transmission experiments in WC475 with and without choke grooves in the flange faces demonstrated that this can noticeably degrade the efficiency (~6% through 11 flanges).

Changing from 4.75” to 6.725” diameter and choosing an optimal gap depth solves this problem without recourse to expensively machined choke flanges.

MAFIA graphic of TE_{12} choke flange used in transmission experiments conducted with KEK in ’99-’00.

Mode-matching simulation of S_{12} for the TE_{12} mode through 11 cascaded flanges.
Propagating Modes in Highly Overmoded Delay Lines

The Cast of Characters

110 mode types (60 TE, 50 TM)

208 modes (114 TE, 94 TM)
(WC475 — 102 modes)

$D = 6.51 \lambda$
(D=10.6 $\lambda$ used for tokomaks)

* — TEmn cyan — in 4.75”
o — TMmn yellow — in 6.725” only
Mode coupling due to small perturbations of the circular waveguide wall can be analyzed by Fourier decomposing the deformation in $\phi$ and then integrating a set of coupled first-order differential equations along $z$. (see e.g. J.L. Doane, "Polarization converters for circular waveguide modes," Int. J. Electronics, 1986, vol. 61, no. 6, pp. 1109-1133.)

$$r(\phi, z) = a + \delta(\phi, z)$$

$$\delta(\phi, z) = a_0^c(z) + \sum_{l=1}^{\infty} \left[ a_l^c(z) \cos l\phi + a_l^s(z) \sin l\phi \right]$$

ordinary polarization:

$$\frac{d}{dz} A_m^o(z) = \sum_{n} \left[ \left( K_{mn}^{oo} a_{p-q}^c(z) + C_{mn}^{oo} a_{p+q}^s(z) \right) A_n^o(z) \right]$$

$$+ \left[ K_{mn}^{ox} a_{p-q}^s(z) + C_{mn}^{ox} a_{p+q}^s(z) \right] A_n^s(z) e^{i\Delta\beta_{mn} z},$$

cross polarization:

$$\frac{d}{dz} A_m^s(z) = \sum_{n} \left[ \left( K_{mn}^{xo} a_{p-q}^s(z) + C_{mn}^{so} a_{p+q}^s(z) \right) A_n^o(z) \right]$$

$$+ \left[ K_{mn}^{xs} a_{p-q}^s(z) + C_{mn}^{xs} a_{p+q}^s(z) \right] A_n^s(z) e^{i\Delta\beta_{mn} z}.$$
Effect of a Constant $\cos 2\phi$ Distortion on $TE_{01}$

$D = 6.725''$ \hspace{1cm} ($a = 8.54075\text{cm}$)

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Effect of Constant \( \cos 2\phi \) and \( \sin 2\phi \) Distortions on \( \text{TE}_{12} \)
Mode rotator geometry and cross-section. The two tapers total 22.86 cm (A second design, which also preserves purity, is 43.50 cm long.). The superposition of the circular cross-section of the ends (red) and the central cross-section (blue) shows the maximum deformation of 6.8%.

Calculated mode amplitude profiles along the polarization converter, or mode rotator, for an entering TE_{12} wave. The asterisks here indicate cross-polarized modes.
Sensitivity of TE$_{12}$ to Constant cos3\(\phi\) (or 5\(\phi\)) Distortions

TE$_{12}$ and TE$_{41}$ are nearly degenerate (beat wavelength = 143m).

The relative phase of the waves changes slowly enough for considerable power to be exchanged even at a small coupling rate.

This parasitic mode was detectable in SLAC/KEK transmission experiment.
Comparison of Sensitivity to Constant $\cos 2\phi$ Distortion
TE\textsubscript{0n}-TM\textsubscript{1n} Degeneracy

TE\textsubscript{01} also has a degenerate mode, TM\textsubscript{11}. TE\textsubscript{02} and TM\textsubscript{12} are also degenerate, as are all TE\textsubscript{0n}-TM\textsubscript{1n} pairs.

Fortunately, the cause of coupling, bending, is easily detected and corrected.

To first order, power coupled to TM\textsubscript{11} in a gently curved waveguide will be returned if the ending axis is parallel to the starting axis.
Any parasitic mode can be a problem if the distortion which couples it to the carrier mode is modulated at the beat frequency $\Delta \beta$.

This effect is utilized in serpentine and ripple-walled mode converters.

Calabazas Creek $\text{TE}_{11}$-$\text{TE}_{12}$ converter.
Wavelengths/Periodicities to Avoid for TE$_{01}$ Transmission
Wavelengths/Periodicities to Avoid for $\text{TE}_{02}$ and $\text{TE}_{12}$ Transmission
Parasitic Mode Coupling at a Discrete Step in Radius
Parasitic Mode Coupling at a Discrete Axis Offset

Effect of an Offset Discontinuity

Fractional Power Loss From Mode

Transverse Axis Offset (inch)
Parasitic Mode Coupling at a Discrete Axis Tilt and at a Discrete $a_2^c$ Discontinuity

(Take with a grain of salt. Checking calculations.)
RF Components
Component Tolerancing

HFSS and Mode-Matching codes are our chief tools for finalizing rf designs. They allow us to simulate geometries and obtain scattering parameters.

For prototype parts, tolerances are kept fairly tight, based on the importance of the dimension, the designer’s feel, and the simulated bandwidth characteristics. This is important since these parts will demonstrate the integrity of the designs.

For manufacture of multiple components, more effort needs to be done to loosen tolerances and lessen cost. This will require multiple runs of the codes, with various dimensions being varied.

Good communication between the rf designers, mechanical engineers, and those overseeing fabrication will facilitate this work.
Some Conclusions

We’ve got analytical tools in place (HFSS, Mode Matching, Mode Coupling) and an understanding of potential sources of efficiency degradation.

Using calculations and measurement results, we will be able to establish more exact tolerances for rf component and delay line fabrication according to an established loss budget.

This will require good communication to maximize savings for a given expenditure of effort.

We will gain useful experience as more components and systems are tested.