SLOT COUPLED BEAM SIGNAL PICKUP DEVELOPMENT AT ARGONNE NATIONAL LABORATORY*

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Introduction

The need for improved concepts for stochastic cooling pickups was recognized and documented during early stochastic cooling studies at CERN.[1] Sensitivity, phase fidelity and construction tolerances are traditionally serious problems in the design of high frequency, large bandwidth devices.

An attractive approach to solving these problems resulted from L. Faltin's[1] work concerning the coupling of TEM to TEM modes through small, common wall apertures. Although aperture coupling of waveguides to other waveguides and to radiation fields has a long established role in microwave tecniques, little work existed concerning TEM coupling.

Recently, H. Lai[2], F. Mills[3] and others have re-examined the characteristics of slot (aperture) coupling to TEM lines. Mills, in fact, developed optimization guidelines for pickups and kickers based on the theoretical model.

Experimental data of slot coupling to TEM lines is very sparse. Furthermore, analytical analysis of the coupling is limited to only a few aperture geometries, and the resulting predictions suffer considerable quantitative uncertainty.

The need for more experimental studies plus the availability of Argonne's pickup test facility[5] motivated an R&D activity for slot couplers at ANL. The goal is to experimentally examine the characteristics of aperture coupled beam signal pickups and to search for designs applicable to stochastic cooling systems.

Slot Coupling Principle

While the analytic treatment of the coupling process is important, it is also valuable to understand it in simple models. Referring to Figure 1, suppose a TEM pulse travels down TEM line 1. As it passes the aperture, the radial $\overline{E}$ field; will "punch thru" to TEM line 2. Similarily, the $\overline{H}$ field from line 1 will "herniate" through the opening to form a flux linkage with line 2. The resulting disturbance on line 2 will propagate from the Z-location of the aperture in both ±Z-directions. It is obvious that the sense of the $\overline{E}$-driven disturbance is such that it aids the "backward" traveling $\overline{H}$-disturbance and reduces the "forward" traveling one. It is also reasonable that the disturbance on line 2 will be rate-sensitive to the pulse on line 1. That is, the signals on line 2 will be proportional to frequency, i.e. the coupling differentiates. In a case where line 1 is a particle beam current, it is suggestive that the disturbance on line 2 due to several, successive apertures would be additive, assuming the pulse velocity on line 2 is about equal to that of the beam.

The wave velocity on line 2 will be reduced in the vicinity of an aperture. This is because the wall series inductance will be increased proportionately more than the shunt capacitance is reduced. Thus for beam velocities near $\beta = 1$, there will, in almost all designs, be an effective phase shift per aperture at any specific frequency. Again, Mills has pointed out that the optimum length of a "coherent" array, from the standpoint of signal coupling, corresponds to a 90° phase shift (signal-to-beam).

All of these plausible characteristics are, in fact, consistent with the results of analytical analysis. Argonne's goal is to test the predictions experimentally.

Early Slot Coupling Tests

Initial tests were performed using 4 mm × 2 mm rectangular slots as the coupling apertures. Tests included single as well as multiple slot plates, and slots whose long dimension was parallel (z) and perpendicular (x) to the beam direction. The geometry is shown in Figure 2.

According to perturbation analysis, the coupled signal is proportional to $m \pm p$, where the + and − are for the forward and backward waves respectively, and

$m \equiv$ magnetic polarizability of the slot

$$\approx 0.216\, \ell_z \ell_x^2 + 0.044\, \ell_x^3 \tag{1a}$$

$p \equiv$ electric polarizability of the slot

$$\approx \pi \ell_x \ell_z^2/16 \tag{1b}$$

where

ℓ_z = aperture size in the beam direction

ℓ_x = aperture size perpendicular to the beam direction

For the apertures used in this initial test the ratio of forward (F) to backward (B) signal

$$\frac{F}{B} \approx \left|\frac{m - p}{m + p}\right|$$

predicted by the perturbation theory is

$$F/B = 0.627 \text{ for the longitudinal slots}$$

and

$$F/B = 0.83 \text{ for the transverse slots}$$

Beam measurements were not consistent with these predictions. For a single transverse slot, F/B was 1.0 ± 0.1 and for a single longitudinal slot F/B was consistent with the existence of no backward wave in serious disagreement with the predictions.

Lab measurements in which two TEM lines were coupled through a single slot confirmed the e-beam results. From these initial measurements and later measurements we have concluded that the electric field coupling appears to be significantly over-estimated by the model, at least for the geometry shown.

Beam measurements of multiple transverse slots of these dimensions yielded a coupling impedance of about 1 Ω/slot at 2 GHz. During these measurements a large coupling impedance, ~ 8 Ω/slot was observed near

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6.5 GHz. This enhancement was related to the resonance of the slot a parameter which set the direction for additional research into higher coupling slot pickups.

Resonant Slot Couplers

In an effort to exploit the enhancement of coupling impedance near slot resonance conditions, we examined various tuning and coupling methods. The most used design was a "dog-bone" shaped slot geometry. Figure 3 shows three such slots in a single plate whose resonant frequencies were measured to be as indicated. One can think of such slots as having most of the inductance lumped in the end-holes, and a parallel capacitor being formed by the small gap of the actual slot. We have found it easy to tune these slots by adjustment of the effective lumped parameters.

Several slot coupled devices have been constructed and tested using slots resonated near 3.5 GHz. The parameters which were normally varied were the characteristic impedance of the TEM lines, the spacing of the TEM lines from the slots, and slot-slot spacing. Figure 4 indicates the phase shift/slot vs. slot spacing for these slots and one particular TEM line. Beam coupling vs. frequency and the additive signal effects are shown in Figures 5 and 6. Although the slots were typically resonant at 3.5 GHz, there was an abrupt fall-off in response of the multi-slot devices above about 2.3 GHz. This phenomenum has been traced to TEM line impedance disturbances near the slots. The resulting, multiple reflections are the source of attenuation at the higher frequencies. We are investigating the nature of these impedance problems with the hope of improving the situation.

Conclusions

The overall performance of slot couplers, at least for frequencies below 2 GHz, can probably not match that of stripline based pickups. A measured, typical coupling at 2 GHz corresponds to about 6-7 ohms/slot-pair and produces about 8° phase shift/slot on the TEM line. Suppose a 12-14 slot array were constructed with these parameters. It would have a total 90° phase shift at about 1.7 GHz, and the coupling would be about 80 ohms at 2.0 GHz. Such an array would be 30 cm long. In a 10 m long straight section, one could place perhaps 25 such modules. After power adding, the net coupling would be about $80 \times \sqrt{25} = 400$ ohms. This is 75% of the value which can be obtained by stripline structures (e.g. the FNAL Tevatron-I design).[4]

On the other hand, stripline structures may be difficult to construct for, let's say, a 4-8 GHz band. Slot coupled devices may then prove to be the more attractive choice. Slot couplers for these higher frequencies will be the subject of our R&D program at this time in the future.

References

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3. "Faltin Pick-up and Kicker System", F. E. Mills, FNAL T#24, December, 1981.

4. "Design Report-Tevatron I Project", Fermi National Accelerator Laboratory, October, 1982.

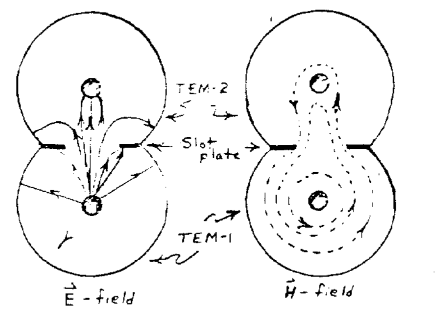


Fig. 1. Highly diagramatic picture of TEM-TEM coupling through a common wall aperture.

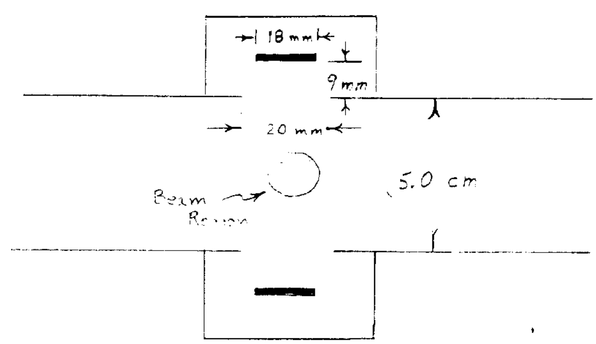
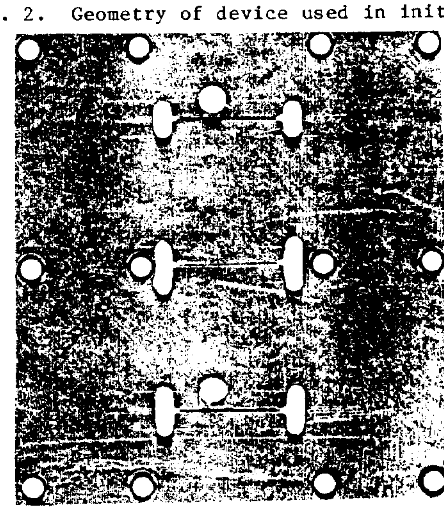


Fig. 2. Geometry of device used in initial tests.



-4.0 GHz

-3.2 GHz

-3.5 GHz

Fig. 3. Three, separately tuned, resonant slots.

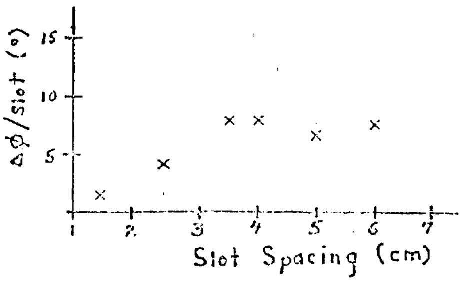


Fig. 4. Phase shift per slot at 2 GHz versus inter-slot spacing (3.5 GHz slots)

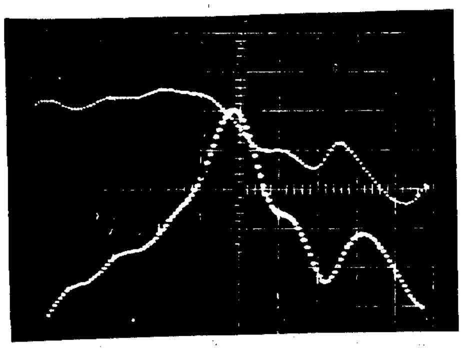


Fig. 5. Measured response of a five-slot coupler in the ANL test facility. Horiz. frequency scale is 0-5 GHz vert scale is 0-50 ohms.

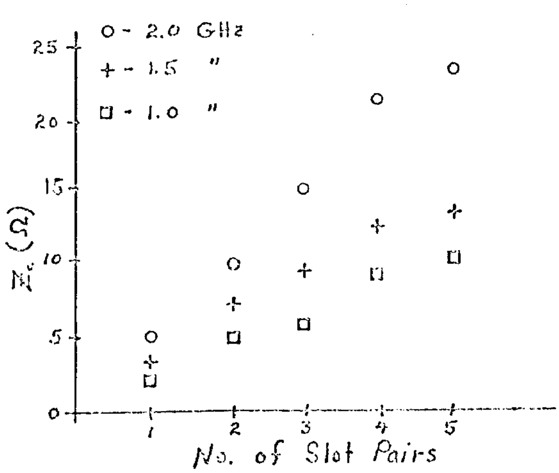


Fig. 6. Addive effects of slots at three different frequencies.