PLANAR SLOTLINE PICK-UPS AND KICKERS FOR STOCHASTIC COOLING

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Abstract

Planar slotline and microstrip configurations on the same dielectric substrate are elements of MICs (Microwave Integrated Circuits). It is proposed to use similar structures for pick-up and kicker applications for stochastic cooling. In this case slotlines on a metallised ceramic substrate (Al_2O_3) are positioned at a given distance from the beam with their axis transversely or at a fixed angle to the image current. The slotlines may be terminated by slotline-microstrip transitions for further combination of the output signals with a microstrip combiner board. Assuming matched transitions, only travelling waves, launched by the image current (Pick-up) occur in the slotlines (Transverse Travelling Wave Structure, TTWS). It seems that in this case, for a single slotline, a high bandwidth (decade) together with good sensitivity can be achieved. An interesting aspect which should be pointed out is that for TTWS of this kind, the sample slice of the beam is tilted and the tilt angle is determined by the propagation constant of the slotline and its orientation relative to the beam. For narrow bandwidth (octave) a transverse standing wave structure (TSWS) might be more effective since higher sensitivities may be obtained. For slotline arrays the lateral distance between the slots is limited by mutual coupling. The frequency range of application is between ca 100 MHz and 30 GHz using present technology on alumina substrates.

Introduction

For pick-up and kicker applications in the GHz range stripline directional couplers or loop structures are widely used. These devices give a high beam coupling impedance over a frequency range of about one octave and can be operated both in the sum and difference modes. Nevertheless, their mechanical construction becomes difficult (microscopic) towards frequencies higher than, say 5 GHz. Therefore, at high frequencies slot pick-ups consisting of a metal plate with an array of slots transverse to the image current are preferred.[1] They exhibit a bandwidth similar to loop pick-ups (resonance of slots) but generally have a lower beam coupling impedance per unit length, their mechanical problems being less severe than those of loop pick-ups. Waveguide-type structures, such as Cerenkov pick-ups and corrugated wall pick-ups have been built, and show a good performance, but have rather small apertures for high sensitivities.

It is the purpose of this paper to discuss a new type of construction consisting of slotlines transverse to the beam (not to be confounded with transverse slots = Faltin type pick-up).[1] The slot pick-up of Faltin may be described as a line propagating a TEM-like wave in the beam direction coupled to the beam by slots in the outer conductor. In contrast to this the slotline pick-up to be discussed here propagates a beam-excited TEM-like wave along a slot between conducting planes perpendicular to the beam direction. The main advantage should be the rather simple fabrication process (double layer planar structure) and thus offering well defined mechanical tolerances. Also due to the photolithographic process very small structures and thus high frequencies can be reached.

Theoretical Model

Consider a charged particle beam (Fig. 1) propagating in +z-direction between two infinite metallic planes at $y = \pm d$. The image current density distribution $\vec{J}_z$ [A/m] may be described as:

$$\vec{J}(y = \pm d) = \vec{u}_z \cdot f(x = \pm d,\ x,\ z,\ t) \qquad (1)$$

$\vec{u}_z$ = unit vector in positive z-direction.

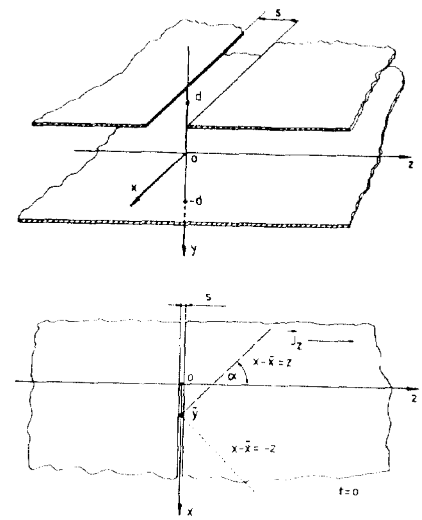

Fig. 1 - Slotlines and beam coordinates.

A transverse (with respect to the beam) slot (width s) of infinite length in ±x-direction in one of the conducting planes (e.g. at $y = \pm d$) could be described in terms of a slotline. This slotline, since it is not (yet) backed by a dielectric material other than vacuum would have a propagation velocity $v_{slot} = c$ (TEM case). For a slotline on a dielectric substrate, in general a frequency dependent propagation velocity $v_{slot}(\omega) < c$ would be obtained. In the following considerations it is assumed that v_{slot}, and also the slotline characteristic impedance Z_L, are independent of frequency (neglecting the dispersion). Thus each current element $\vec{J}_z$ would "see" two parallel resistors Z_L and launch waves in ±x-directions. The voltage across the slotline V_s then turns out to be:

$$V_s = J_z \cdot dx_0 \cdot Z_L/2 \qquad (2)$$

assuming J_z not to be perturbed by the slot.

As a first approximation we assume that for a single current element at a source point $y = d, x_0, 0$, J_z may be written as:

$$\vec{J}(d, x_0, 0, t) = \delta(x_0) \cdot f(t)\vec{u}_z = g(y{=}d, x, z, t) \cdot \vec{u}_z \,. \qquad (3)$$

Let us remark that:

$$J(d, x_0, 0, t) = J(d, x_0, z, t + z/v_{beam})$$

whatever J is, an observer at any position $y{=}d, x,\ z{=}0, t$ sees:

$$V_s(x,t) = \frac{Z_L}{2} \int_{-\infty}^{+\infty} J\left(x_0,\ t - \frac{|x - x_0|}{v_{slot}}\right) dx_0 \qquad (4)$$

rewritten as:

$$V_s(x,t) = \frac{Z_L}{2} \int_{-\infty}^{x} dx_0 \; J\left(x_0,\; t - \frac{x - x_0}{v_{slot}}\right) + \frac{Z_L}{2} \int_{x}^{+\infty} dx_0 \; J\left(x_0,\; t + \frac{x - x_0}{v_{slot}}\right) \quad . \qquad (5)$$

With the present assumption the image current distribution $g(y=\pm d, x, z, t)$ and the transversely ($\pm x$) travelling waves in the slotlines are propagating both with $v = c(v_{beam} = v_{slot} = c)$ perpendicular to each other. The observer at y will measure a voltage across the slotline which has been raised from an image current distribution along the line:

$$x - x_0 = z \cdot v_{slot}/v_{beam}$$

(dashed line in Fig. 1) for slotline waves in +x direction and

$$x - x_0 = -z \cdot v_{slot}/v_{beam}$$

(dotted line in Fig. 1) for slotline waves in -x direction.

Thus by separating the +x and -x travelling slotline waves one obtains at a given time t the superposition of an image current distribution along a ±45° line (Fig. 1) if $v_{beam} = v_{slot}$ or more generally:

$$tg\alpha = \frac{v_{slot}}{v_{beam}} \qquad (6)$$

Under the further assumption that each surface current element can be attributed only to charged particles travelling perpendicularly above or below it, one might interprete the signal $V_s(x,t)$ as being raised from a particle population in two sample disks of the beam tilted by $\pm\alpha$ to the z-axis. Separating the +x and -x propagating slotline wave (e.g. by measuring $V_s(x,t)$ at a distance x where $|\vec{J}_z| \approx 0$) a pick-up signal corresponding to a single tilted sample disk of the beam can be found.

Experimental Slotline Pick-Up Structures

The first mask, which was used to investigate the properties of a slotline pick-up, is reproduced in Fig. 2. It contains one line with Z_L = 150Ω, 3 lines Z_L = 100Ω and 3 lines Z_L = 50Ω on a 3 mm alumina substrate. The impedances were calculated for f = 1.5 GHz. Slotline-coaxial cable transition are provided at each end of the slotline, soldering a semirigid cable on the metallised substrate surface with the inner conductor across the slot next to the circle (= open end). For the realisation of all masks shown here, the "MICROS 3" CAD programme[2] has been used. It turned out that already for this very simple approach reasonable electrical properties could be obtained and that this structure is well suited to investigate the mutual coupling between slotlines, effects of mismatches, radiation and attenuation[3,4] with two transitions to 0.141" semirigid cable. The S-parameter S_{11} (reflexion coefficient) and S_{21} or S_{12} (transmission coefficient) are defined as the complex ratio of the reflected wave/incident wave and transmitted wave/incident wave, respectively. In the frequency range 1-4 GHz the transmission characteristic is reasonably flat and about half the transmission loss (ca 1 dB) can be explained by mismatch (-10 dB).[4] Since the transmission loss amounts to roughly 3 dB/m here[5], the radiation loss would be below 0.2 dB (2 dB/m). It should be pointed out that the intended interaction mechanism with the beam is not due to radiation (since slotlines or slots are often used as radiating elements in antenna arrays). It rather works like a transformer, where the image current produces some voltage in a given load.

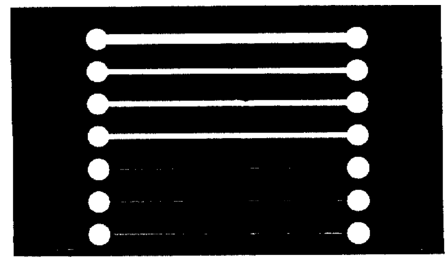

Fig. 2 - Mask for experimental (transverse travelling wave) slotline pick-up.[4]

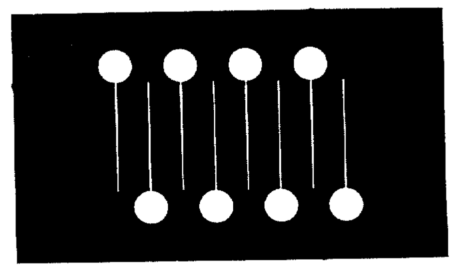

Fig. 3 - Mask for experimental (transverse standing wave) slotline pick-up (f_0 = 1.5 GHz).[4]

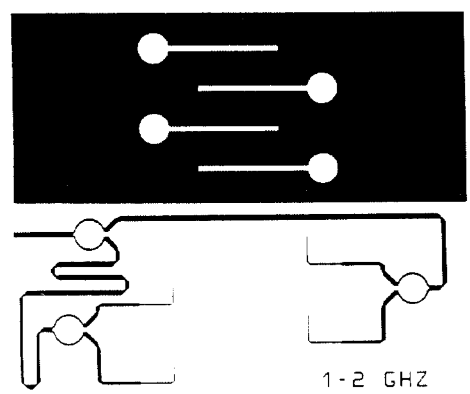

Fig. 4 - Mask for staggered standing wave slotline pick-up (4 × 100Ω; f_0 = 1.5 GHz); microstrip combiner board (right).

If more than one slotline is provided, mutual coupling will take place. The directivity turns out to be about 10-15 dB (1-4 GHz) and the forward coupling gives a relatively flat response in the same frequency range. A good theoretical treatment of slotline couplers can be found in references [5], [6] and [7].

For measurements of the pick-up response the field of a beam is simulated by a wire closely mounted (≈ 2 mm) above a conducting ground plate which forms a 50Ω transmission line, where most of the energy is concentrated between the wire and the ground plate. For quantitative calibration reference measurements were carried out with 50Ω and 100Ω λ/4 loop (or stripline) pick-ups positioned at the same distance h (h > 10 mm) from the ground plate as the slotline metallisation. Here the structure from Fig. 3 was mainly looked at, because resonant slotlines give a response more similar to loop pick-ups than travelling wave slotlines. The length of these slots in Fig. 3 approaches λ/2 at 1.5 GHz, Z_0 = 50Ω. For an image current element passing in the middle of that array, each short circuit transforms into an open one at λ/4 distance from the short circuit and the entire structure should have an impedance of 8 × 50Ω for this image current element. Considering a beam close to the surface in the middle of the array, one may assume that nearly all the image current is passing over the slotline at $x = 0$ (Fig. 1), thus resulting in a powerextraction of $I^2_{beam}/4 \times 400\Omega$ which is equivalent to a beam coupling impedance of 100Ω for a single pick-up plate. The results of these measurements (Fig. 5) prove that a single resonant slotline (TSWS) has a pick-up response shape comparable to a single λ/4 loop (centred beam). If the outputs of either side are combined in a 4 to 1 power combiner (proper delay for each output provided), a smoothing effect can be found (Fig. 6) and slight losses due to the combining network have to be accepted. For an off-centred beam, however, one might obtain deep notches in the response characteristic due to interference effects on the slotline (v_{slot} is only ≈0.5 c). The shape of the curves in Fig. 6 were also confirmed by measurements carried out at Argonne National Laboratory with a 22 MeV electron beam.[8] For these measurements the distance of the beam from the pick-up plate was 15 mm and with the combined signals of the 8 slotlines the maximum coupling impedance was found to be about 50Ω. The missing factor 2 (or 3 dB) can be attributed partly to losses in the 8:1 power combiner (≈ 1 dB) and 8 times 2 metre coaxial cable. The other part is due to the fact that not all the image current passes over the centre of the slotline since the beam is already 15 mm apart.

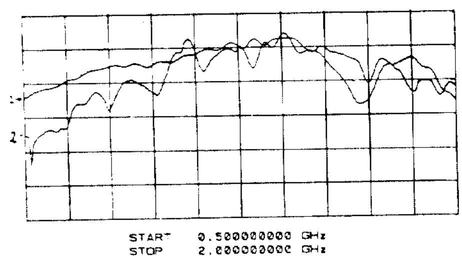

Fig. 5 - Pick-up response of a 50Ω λ/4 loop (2) and a single 50Ω resonant slotline (1) simulated beam centred (vert. scale: 5dB/div).

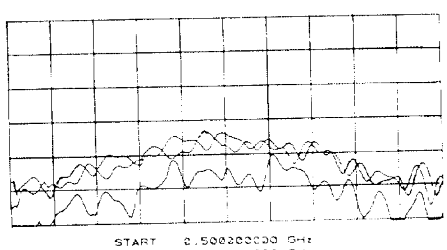

Fig. 6 - Pick-up response of λ/4 loop (lower trace) and 4 combined resonant slotlines (Fig. 2) of either side (upper trace); simulated beam centred (vert. scale: 5dB/div).

The staggered slotlines (100Ω) in Fig. 4 have been realised in conjunction with a microstrip combiner board containing Wilkinson power combiners. Microstrip-slotline transitions with a through hole were applied in this case. A distinct ripple and rather poor sensitivity (compared with results from Fig. 6) is a difficulty linked to staggered slotlines. But with an average signal level 6 dB above the response of a single λ/4, 100Ω loop approximately the same beam coupling impedance per unit length in the frequency range 1-2 GHz as such a loop has been obtained.

Conclusion

The theoretical and measured results on planar slotline pick-ups indicate that these structures might become an interesting alternative to both the well known stripline or λ/4 loop pick-ups as well as th slot pick-ups on Faltin type structures.

Present fabrication methods allow very small dimensions in the surface pattern on the alumina substrate. The process involved is relatively easy and returns a good reproducibility with tight tolerances.

Resonant slotlines (TSWS) could have a higher beam impedance than stripline λ/4 loops for a centred beam, but for an offset beam a faster lateral decay in sensitivity should be taken into account. Resistive losses are about comparable to loop pick-ups. Travelling wave slotlines (TTWS) offer the possibility of various sample choices on the beam. For a transverse slotline with v(slot) = c/2 and a beam (v(beam) = c) the normal vector of the sample disk would be at 26.6° to the beam axis (45° for v(slot) = c). By changing the angle of the slotline a wide range of angles of the sample disk can be set. Since the slotline must not necessarily be straight a variety of sample disks may be chosen. For a TTWS the beam diameter is not limited to about λ/2 at the center frequency since the slotlines interact mainly with the TEM-like wakefield of the beam. Possible waveguide modes in the beampipe may be suppressed by means of absorbing material.

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References

[1] L. Faltin, Slot-Type Pick-up and Kicker for Stochastic Beam Cooling, CERN/ISR-RF/77-47, 1977.

[2] J.F. Zurcher, "MICROs 3" A CAD/CAM Program for Microstrip Circuits EPFL Lausanne-LEMA, 1985.

[3] F. Caspers, A Broadband Slotline Pick-up, PS/AA/ACOL Note 31, CERN, Feb. 1985.

[4] F. Caspers, Planar Slotlines, Pick-ups and Kickers for Stochastic Cooling, CERN/PS/85-48 (AA), Aug. 1985-June 1986.

[5] R.K. Hoffmann, Integrierte Mikrowellenschaltungen, Springer Verlag 1983.

[6] K.C. Gupta, R. Garg and I.J. Bahl, Microstrip Lines and Slotlines, Artech House 1979.

[7] M. Aikawa and H. Ogawa, A New MIC Magic-T Using Coupled Slotlines, IEEE-MTT-28 No 6, June 1980, pp. 523-528.

[8] D. Suddeth, Argonne National Laboratory, Private Communication.