3D-FINITE DIFFERENCE ANALYSIS OF PLANAR LOOP COUPLERS AS BEAM ELECTRODES IN STOCHASTIC COOLING SYSTEMS

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Abstract

Loop couplers are used for the interaction with the beam as pickups and kickers in stochastic cooling systems. This paper presents a new planar loop coupler based on Al_2O_3 as dielectric substrate and discusses both the signal-beam interaction and the scattering behaviour of the coupler working as a kicker. The planar concept is analyzed by means of a 3-d full-wave finite-difference method in the frequency domain and the results are compared to the image current approach, which is commonly used for coupler design.[1]
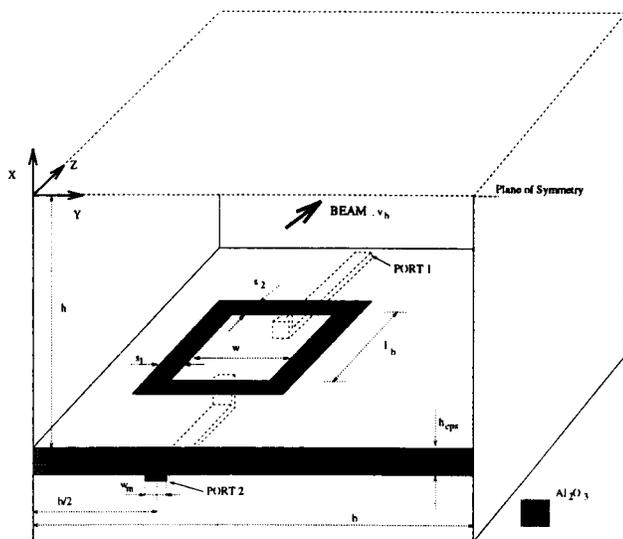
Figure. 1. Lower Half of a Planar Loop Coupler Doublet with $b = 70 \text{mm}, h = 15 \text{mm}$

I. INTRODUCTION

In the stochastic cooling system of GSI, Darmstadt both for detection and deflection of the beam conventional loop couplers [1] will be used as pickup and kicker device, respectively. In order to ensure sufficient efficiency an array of 16 coupler quadrupols has to be incorporated into the storage ring. Their main drawback is the rather complicated mechanical fabrication.

First experiments already were performed on so-called planar loop couplers [2] for a system frequency range of 4-8GHz and on teflon as dielectric material. Their main advantage is the ease

of fabrication, since standard techniques of planar transmission lines for high-frequency circuit applications can be used.

This paper presents results on a planar loop coupler, which is designed particularly for the environment of the stochastic cooling system in the particle storage ring of GSI (frequency range: 0.9-1.6GHz, f_{mid}=1.25GHz). Thus, in order to satisfy the UHV requirements Al_2O_3 is used instead of teflon [2].

II. METHOD OF ANALYSIS

For analysis on one hand the 'doublet configuration' as shown in fig. 1 is considered, which consists of two planar couplers placed above and below the beam. Connecting two doublets with the distance l_d (coupler to coupler) of a microstrip on the backside of the substrate in series leads to the 'super-doublet configuration', which is also under investigation.

The simulation itself is restricted to kicker operation for longitudinal beam cooling (even mode operation), when the coupler is fed at the upstream microstrip port 1 since, based on this analysis, both to the signal-beam interaction for vertical cooling and for pick-up operation can be derived [3].

The interaction of the deflecting electromagnetic field and the particle beam is described by means of a so-called kicker constant $\vec{K}(\omega, x_b, y_b)$, which assumes the beam to be a single charge travelling in position (x_b, y_b) along the z-axis and takes into account different beam and signal velocities (v_b and v_s, respectively).

$$\vec{K}(x_b, y_b, \omega) = \int\limits_{-\infty}^{+\infty} (\vec{E}(x_b, y_b, z, \omega) + \vec{v_b} \times \vec{B}(x, y_b, z, \omega)) e^{j\frac{\omega z}{v_b}} \, dz$$

(1)

The electromagnetic field is calculated by means of a full-wave analysis applying the 3-d finite-difference method in the frequency domain. Thus, in contrast to the common image current approach effects such as field fringing at the end and beginning of the coupler, are taken into account. Furthermore, the same fieldtheoretical approach leads to the reflection and transmission coefficients of the complete 3-d configuration (S_{11} and S_{21}, respectively).

III. IMAGE CURRENT APPROACH

For the design of conventional loop couplers the image current approach is often applied, which analyzes the pick-up instead of the kicker. This approach can also be used for planar couplers, if one takes into account different beam and signal paths along the coupler:

- while the beam is travelling parallel to the z-axis along the coupler (length l_b) the signal is running along two bent parallel slot lines each of length $l_s = l_b + w$ (see fig. 1).

Thus, to determine the frequency dependent coupling between the beam and the microstrip ports the single coupler can be replaced by two slot lines in parallel. Since the beam exites an image current on the surface of the coupler, the slot lines are driven by current sources, which differ only by a factor $e^{-j\omega l_s/v_b}$.

Following this principle the equivalent circuit of a super-doublet configuration can be derived (see fig. III) and the respective output voltage on the downstream port 2 can be determined (Eqn. 2).

Figure. 2. Equivalent Circuit of two planar couplers in series with distance l_d combined by a microstrip line of length l_c (Super-Doublet); with $I_1 = I_0 e^{-j\omega l_b/v_b}$, $I_2 = I_1 e^{-j\omega l_d/v_b}$, $I_3 = I_2 e^{-j\omega l_b/v_b}$
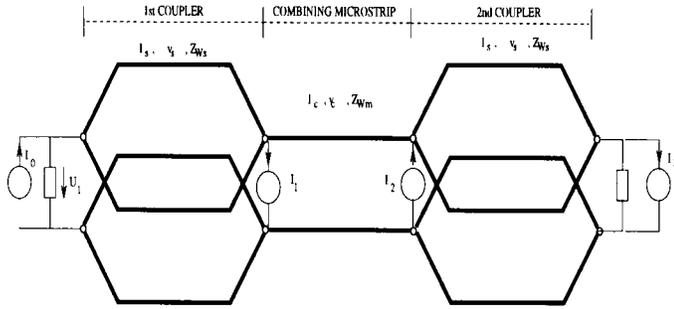
$$I_3 = I_2 e^{-j\omega l_b/v_b}$$

$$U_1 \sim \sin\left(\frac{\omega l_s}{2v_s} + \frac{\omega l_b}{2v_b}\right)\cos\left(\frac{\omega l_c}{2v_c} + \frac{\omega l_d}{2v_b} + \frac{\omega l_s}{2v_s} + \frac{\omega l_b}{2v_b}\right) \quad (2)$$

In Eqn. 2 the first factor represents the frequency dependent coupling of a single electrode, while the second one includes the typical characteristic due to the combination of two couplers in series.

The design of a super-doublet configuration is generally governed by the objective to ensure maximum interaction at midband frequency f_{mid}. As can be seen from Eqn. 2, this will be reached if the length l_b of the single coupler is given by:

$$l_b = \left(\frac{v_s}{2f_{mid}} - w\right)/\left(1 + \frac{v_s}{v_b}\right) \quad (3)$$

ensuring optimum coupling of the single coupler at f_{mid}
and, furthermore, if the length l_c of the combining microstrip is given by:

$$l_c = \frac{v_c}{f_{mid}} - \left(\frac{v_c l_g}{v_b} + \frac{v_c l_s}{v_s} + \frac{v_c l_b}{v_b}\right) \quad (4)$$

which doubles coupling efficiency at f_{mid}.

The trick of this approach is the possibility to derive the coupling behaviour without any fieldtheoretical simulations and only by means of the transmission line characteristic, which can be taken from standard books dealing with analysis of transmission lines (e.g.:[4]). However, it should be pointed out, that this approach generally neglects both fringing fields due to the 3-d structure of the coupler and displacement currents.

IV. FIRST DESIGN

Considering the single coupler as succeeding junctions from microstrip- to slot- to microstrip-line minimum reflection requires matching of the respective characteristic impedances:

$$Z_{w_m} = \tfrac{1}{2}Z_{w_s}$$

wherein Z_{w_s} refers to the characteristic impedance of this slotline part which runs parallel to the z-axis.

Therefore, assuming a particular substrate height h_ϵ and the restriction of Z_{w_m} to 50Ω both the microstrip width and slotwidth were determined by means of a 2-d finite difference analysis. On the other hand several 3-d simulations were necessary to optimize first the length l_b of a doublet and then the length l_c of the combining microstrip line of the super doublet configuration in order to ensure maximum coupling at f_{mid}.

For this first design uniform slotwidths were assumed, i.e.: $s_{s1} = s_{s2}$ (see fig. 1).
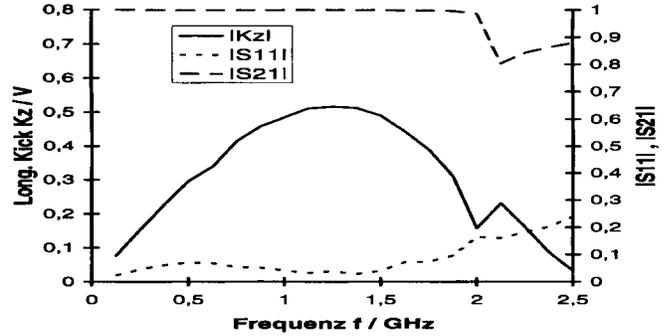
Figure. 3. Doublet in even mode operation with $(x_b, y_b) = (0, (b/2)), s_1 = s_2 = 3.0\mathrm{mm}, w_m = 2.0\mathrm{mm}, h_\epsilon = 2.5\mathrm{mm}, l_b = 26\mathrm{mm}$

Fig. 3 and Fig. 4 present the results of the 3-d fullwave simulations.

They demonstrate that an electrode length of $l_b = 26\mathrm{mm}$ and a length of the combining microstrip $l_c = 38\mathrm{mm}$ lead to a very good optimization of the maximum coupling at midband frequency f_{mid} for the doublet and super-doublet configuration, respectively. In comparison, applying the image current approach (Eqn. 3, Eqn. 4) gives the respective length dimensions as:

$$l_b = 23.6\mathrm{mm}, l_c = 32.6\mathrm{mm}$$

and leads to a deviation from the 3-d simulation of less than 15%.

On the other hand figs. 3 and 4 also demonstrate the weak scattering behaviour, particularly of the super doublet:

- at the upper frequency limit of the system frequency band $f_{up} = 1.6\mathrm{GHz}$ 33% of the power fed into the upstream microstrip port of the super-doublet is reflected.

V. REDESIGN

In order to reduce the reflection coefficient S_{11} a redesign had to be performed. In the first design the characteristic impedance of the microstrip line was matched to the characteristic impedance of the part of the slotline which runs in parallel
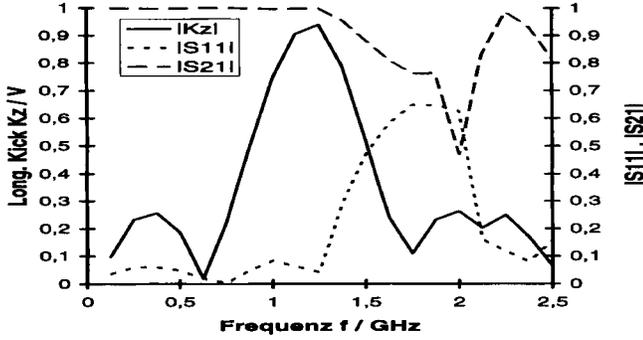
Figure. 4. Super-Doublet in even mode operation with $(x_b, y_b) = (0, b/2), s_1 = s_2 = 3.0\text{mm}, w_m = 2.0\text{mm}, h_\epsilon = 2.5\text{mm}, l_d = 28\text{mm}, l_c = 38\text{mm}, l_b = 26\text{mm}$

to the z-axis. From this point of view the part of the slot line, which is in parallel to the y-axis can be considered - in combination with the via hole - as a discontinuity which might cause additional reflections.

Therefore, in the redesign the constraint of equal slot dimensions was dropped and the optimum width of the horizontal slot s_2 for minimum reflection was investigated.

Furthermore in the first design the length of the combining microstrip l_c between the couplers in series was chosen to be larger than the coupler-coupler distance including substrate height ($l_c > l_d + 2h_\epsilon$). This causes further reflections, since the combining microstrip has to be bent. Thus, to minimize the number of bends in the redesign the combining microstrip was chosen to

$$l_c = l_d + 2h_\epsilon. \tag{5}$$
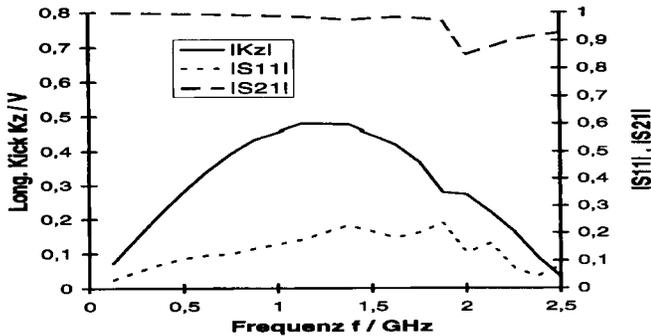
Figure. 5. Doublet in even mode operation, with $(x_b, y_b) = (0, b/2), s_1 = 3.0\text{mm}, s_2 = 1.75\text{mm}, w_m = 1.6\text{mm}, h_\epsilon = 2.0\text{mm}, l_b = 28\text{mm}$

As can be seen from fig. 5, the maximum coupling of the single coupler is exactly adjusted to midband frequency if the electrode length l_b is equal to 28mm. In comparison the image current approach Eqn.3 deviates less than 15% ($l_b = 24.9\text{mm}$) from the fullwave analysis.
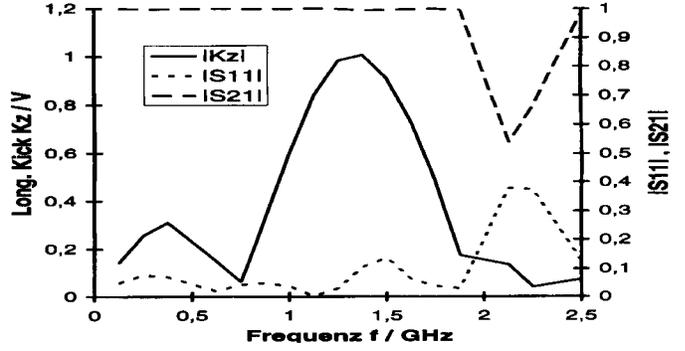
Figure. 6. Super-Doublet in even mode operation; with $(x_b, y_b) = (0, b/2), s_1 = 3.0\text{mm}, s_2 = 1.75\text{mm}, w_m = 1.6\text{mm}, h_\epsilon = 2.0\text{mm}, l_d = 20\text{mm}, l_c = 24\text{mm}, l_b = 28\text{mm}$

On the other hand the maximum coupling of the super doublet is reached at a higher frequency than f_{mid}. This deviation is due to a slight mismatch of the length of the combining microstrip l_c and the distance between the two couplers l_d, but seems to be still acceptable.

However, both fig. 5 and fig. 6 show a strongly reduced reflection of the power fed into the upstream port,i.e.: at the maximum, 2% of the power is reflected in the redesigned coupler within the system frequency band.

VI. CONCLUSION

The fullwave analysis of planar loop couplers using Al_2O_3 as substrates show that the following design aspects are to be taken into account to avoid reflections:

1. Different slot dimensions have to be used ($s_1 \neq s_2$)
2. Bends of the combining microstrip of super-doublets are to be avoided leading to Eqn.(5)

Furthermore, it was shown that the design of the planar coupler applying a modified image current approach is to be considered as a useful first approach. The error due to neglected fringing fields was found to be less than 15%.

References

[1] Raabe P., Heinrich W., Hartnagel H.: Rigorous Computer Analysis of High Frequency Pickup and Kicker Devices for ESR Stochastic Cooling. Conf. Prc. EPAC 1992 (Berlin); pp919-921.
[2] McGinnis D.; et.al.: Design of 4-8GHz Bunched Beam Stochastic Cooling Arrays for the Fermilab Tevatron. Conf.Proc. IEEE PAC 1991, pp.1389-1391
[3] Lambertson G.: Dynamic Devices - Pickups and Kickers. AIP Conf.Proc. 153, New York (1987), pp.1414-1427.
[4] Hoffmann R.K.: Integrated Microwave Circuits. Springer Verlag 1983.