PICKUP DESIGN WITH BETA MATCHING *

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Abstract

The main goal of this project is to investigate the Schottky noise of an ion beam in the frequency range from 3 to 5 GHz. In order to accomplish this task, a pickup design is required. For an efficient study of this Schottky noise the pickup sensitivity for low beta must be increased. A design for such a problem has been developed in [1] for a fixed beam velocity but can also be used for variable beta by using a tunable material (ferroelectric) inside the waveguide. Since such tunable materials like for instance BST (Barium Strontium Titanate) are lossy, the impact of dielectric losses on the pickup sensitivity will also be investigated in this work. Additionally to the classical parameter studies where multiple simulation runs based on the original numerical model are initiated to characterize the various design parameters it is also possible to utilize a reduced model instead. In particular one is interested in a fast evaluation of the frequency response while taking also material variations into account. In this work, a multivariate parameterized dynamical system is set up and used complementary to the full model for the required beam characterization.

INTRODUCTION

The increasing of the pickup sensitivity for beams moving with a velocity below the speed of light is the main motivation of this project. However the design to develop for this purpose must be operational for variable beam velocities. This leads to the use of a tunable material in the waveguide to match the phase velocity of the wave to the beam velocity (see figure 1). In the first part of this work the simulation results of the structure depicted in figure 1 will be presented while the second part will be based upon the MOR (Model Order Reduction) as mentioned in the abstract.

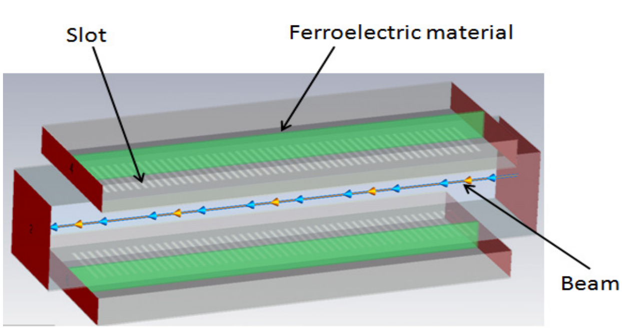

Figure 1: Pickup design for variable beta from [3].

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SIMULATION RESULTS

Starting from a design for a fixed beta presented in [1], we will present in this part of the paper the simulation results relative to the enhancement of the pickup sensitivity for variable beam velocities as well as the effect of dielectric losses on the transfer impedance of the system.

Pickup Sensitivity for Variable β

The pickup sensitivity is represented by the transfer impedance, which is defined for longitudinal pickups as follows [4]:

$$Z_T = \frac{U}{I_b}, \tag{1}$$

where U and I_b are the output voltage and the beam current, respectively. The transfer impedance for different beam velocities is shown in figure 2. The dimensions of the design depicted in figure 1 are chosen such that the response of the system be at 3 GHz for a beam velocity equals $0.75 * c_o$, where c_o stands for the speed of light. $\epsilon_r = 50$ used in the simulation as dielectric constant of the ferroelectric doesn't reflect the reality. This value is used only to test the tunable principle but in reality the permittivity of these materials is very high as mentioned in the next section.

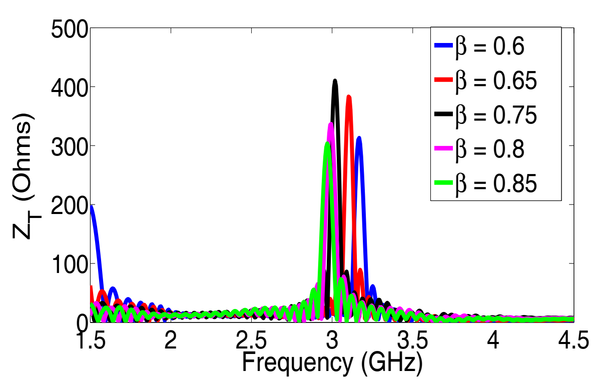

Figure 2: Transfer impedance for different beam velocities. The relative permittivity of the ferroelectric ϵ_r = 50

In figure 2 we can see that for different beam velocities calculated with CST PARTICLE STUDIO ® [3], the system responds at different frequencies as expected. To explain this difference we have to look at the phase velocity v_p of the propagating wave in the fundamental mode TE_{10} of an unperturbed hollow waveguide, whose width a is greater than its height b.

$$v_p = \frac{\omega}{\sqrt{\left(\frac{\omega\mu_r\epsilon_r}{c_o}\right)^2 - \left(\frac{\pi}{a}\right)^2}} \quad (2)$$

In Eq. (2), $\omega = 2\pi f$, where f is the frequency of the wave. μ_r and ϵ_r represent the relative permeability and permittivity of the material inside the waveguide, respectively. This phase velocity as a function of the normalized frequency is presented in figure 3.

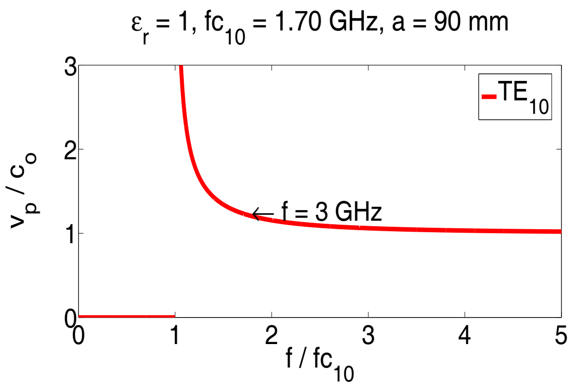

Figure 3: Normalized Phase velocity of a propagating wave in the fundamental mode TE_{10} of an unperturbed hollow waveguide

In the above figure it is clear to see that, the greater the frequency the lower the phase velocity of the wave. Taking into account that the phase velocity of the frequency 3 GHz is matched to the beam velocity $\beta = 0.75$, the response of the system for a beta unequals 0.75 should be at a frequency different from 3 GHz. In order to get the response of the system at 3 GHz for instance for beta below 0.75, one has to slow down the wave in the waveguide. This corresponds to an increasing of the relative permittivity ϵ_r, while for beta above 0.75 ϵ_r must be decreased. For instance for $\beta = 0.6$ and $\beta = 0.85$, the relative permittivity ϵ_r must be equal to 55 and 48 respectively, to get the response at 3 GHz, as we can see below in figure 4 and 5.

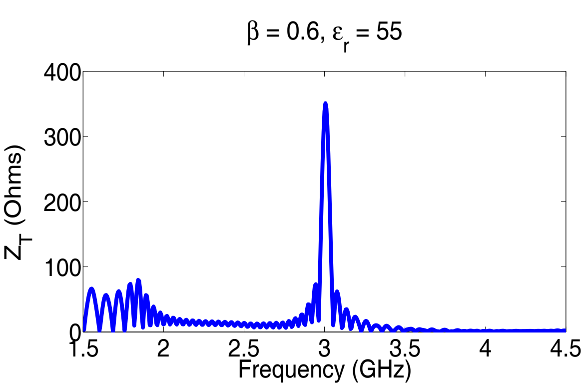

Figure 4: Velocity matching for $\beta = 0.6$

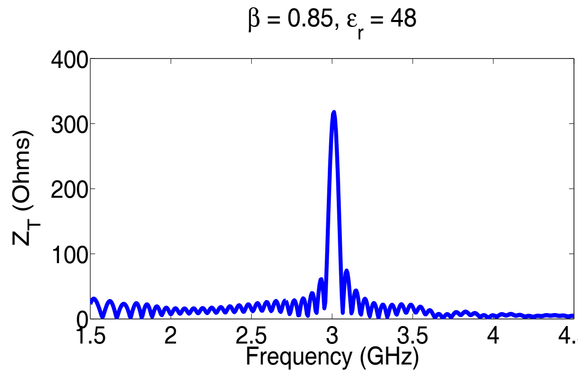

Figure 5: Velocity matching for $\beta = 0.85$

Impact of Dielectric Losses on the Sensitivity

In this section the dielectric losses in the ferroelectric are studied at 3 GHz for $\beta = 0.75$ to see their impact on the sensitivity of the system. Ferroelectric materials are typically nonlinear dielectrics. One of the many characteristics of such materials is the distinct dependency of their permittivity on the intensity of an applied electric field [6]. The dielectric constant of these materials are invariably very high, on the order of thousands to tens of thousands [6]. The most suitable ferroelectric for microwave applications is Barium-Strontium-Titanat (BST), which in the presence of an external applied DC-field exhibits a maximum tunability reaching 80 percent [2]. The dielectric losses are described by the so called loss tangent, which is defined as [6]:

$$tan\delta = \frac{\sigma}{\omega\epsilon_o\epsilon_r}, \quad (3)$$

where σ and ϵ_o signify the conductivity of the material and the permittivity of free space, respectively. The transfer impedance of the design presented in figure 1 is shown below for different loss tangent at 3 GHz.

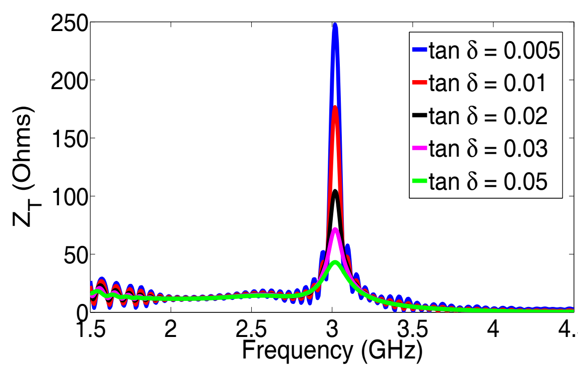

Figure 6: Transfer impedance for $\beta = 0.75$ with different loss tangent at 3 GHz.

In the above figure it is clear to see that the transfer impedance considerably decreases with increasing loss tangent at 3 GHz. Comparing these results with that without loss tangent (look at $\beta = 0.75$ in figure 2) and assuming that the minimum reachable loss tangent be 0.005, the reduction in transfer impedance then corresponds to at least arround 40 percent. For this reason the tunable material to use for this design must have a very low loss tangent, for instance Strontium Titanate, whose minimum reachable loss tangent in the frequency range 1...10 GHz is arround 0.002 [5].

PARAMETRIC MODEL ORDER REDUCTION

The particle beam velocities in the beam pipe can be modeled by respective permittivities ε_i. Different resonance curves result for each ε_i. With an appropriate $\varepsilon_{\text{tune}}$ for the tunable material, the resonance frequency can be again shifted to $f = 3$ GHz. The appropriate $\varepsilon_{\text{tune}}^{3\,GHz}$ can be characterized by performing a parameter sweep in CST MWS over a relatively wide range of $\varepsilon_{\text{tune}}$ in order to restrict the search range. The exact $\varepsilon_{\text{tune}}^{3\,GHz}$ is found by doing an optimization in MWS over this small range. The time consuming parameter sweep in MWS can be replaced by multivariate MOR techniques.

This method uses the Maxwell Grid Equations (MGE) which describe the device and which have been obtained by using the Finite Integration Technique [7]

$$\begin{aligned} \mathbf{C}_{\text{FIT}}\widehat{\mathbf{e}} &= -\tfrac{\mathrm{d}}{\mathrm{dt}}\mathbf{M}_\mu\widehat{\mathbf{h}}, & \mathbf{S}_{\text{FIT}}\mathbf{M}_\mu\widehat{\mathbf{h}} &= 0, \\ \widetilde{\mathbf{C}}_{\text{FIT}}\widehat{\mathbf{h}} &= \tfrac{\mathrm{d}}{\mathrm{dt}}\mathbf{M}_\epsilon\widehat{\mathbf{e}} + \widehat{\widehat{\mathbf{j}}}_s, & \widetilde{\mathbf{S}}_{\text{FIT}}\mathbf{M}_\epsilon\widehat{\mathbf{e}} &= 0. \end{aligned} \tag{4}$$

The matrices $\mathbf{C}_{\text{FIT}}, \widetilde{\mathbf{C}}_{\text{FIT}}$ and $\mathbf{S}_{\text{FIT}}, \widetilde{\mathbf{S}}_{\text{FIT}}$ are discrete topology matrices representing the curl and divergence operators, respectively. The $\mathbf{M}_\varepsilon, \mathbf{M}_\mu$ are diagonal matrices which contain the mesh geometry and the material properties. The MGE are used to define a system with input $\mathbf{i}$, output $\mathbf{u}$, a state vector $\mathbf{x}$ and system matrices $\mathbf{A}, \mathbf{B}, \mathbf{C}$. This can be achieved by substituting $\widehat{\mathbf{h}}$ in (4), resulting in

$$\underbrace{\left(\mathbf{M}_\varepsilon s^2 + \widetilde{\mathbf{C}}_{\text{FIT}}\mathbf{M}_\mu^{-1}\mathbf{C}_{\text{FIT}}\right)}_{\mathbf{A}(s,\varepsilon_{\text{tune}})}\widehat{\mathbf{e}} \quad = \quad -s\widehat{\widehat{\mathbf{j}}}_s \tag{5}$$

in the frequency domain. The input at the ports are defined in terms of a matrix $\mathbf{B}$ and the generalized current $\mathbf{i}$, i.e. $-\widehat{\widehat{\mathbf{j}}}_s = \mathbf{Bi}$. In addition, $\widehat{\mathbf{e}}$ represents the state vector, thus $\mathbf{x} = \widehat{\mathbf{e}}$. Analogously, the output is defined in terms of the vector $\mathbf{x}$ and a matrix $\mathbf{C}$. The resulting system is

$$\mathbf{A}(s, \varepsilon_{\text{tune}})\mathbf{x} = s\mathbf{Bi}, \quad \mathbf{u} = \mathbf{Cx}, \tag{6}$$

with transfer function $\mathbf{Z}(s, \varepsilon_{\text{tune}}) = \mathbf{CA}^{-1}(s, \varepsilon_{\text{tune}})\mathbf{B}$. MOR aims to reduce this typically very large n dimensional system (6) to an $m \ll n$ dimensional system.

For this, the solution vector $\mathbf{x}$ of (6) is restricted on a space spanned by orthonormal trial vectors $\mathbf{v}_1 \ldots \mathbf{v}_m$. With $\mathbf{V} = [\mathbf{v}_1 \ldots \mathbf{v}_m]$ we substitute $\mathbf{x} = \mathbf{V}\hat{\mathbf{x}}$.

$$\hat{\mathbf{A}}\hat{\mathbf{x}} = s\hat{\mathbf{B}}\mathbf{i}, \quad \mathbf{u} = \hat{\mathbf{C}}\hat{\mathbf{x}} \tag{7}$$

with $\hat{\mathbf{A}} = \mathbf{W}^*\mathbf{AV}$, $\hat{\mathbf{B}} = \mathbf{W}^*\mathbf{B}$, $\hat{\mathbf{C}} = \mathbf{CV}^*\mathbf{B}$ and transfer function $\hat{\mathbf{Z}}(s, \varepsilon_{\text{tune}}) = \hat{\mathbf{C}}\hat{\mathbf{A}}^{-1}(s, \varepsilon_{\text{tune}})\hat{\mathbf{B}}$. The matrices $\mathbf{V}$ and $\mathbf{W}$ are chosen such that the moments of the original and the reduced order transfer functions are matched with respect to both s and $\varepsilon_{\text{tune}}$. The procedure is described briefly in [8] and in more detail in [9].

Once the projection matrices are set up, which is the most time consuming part in MOR, the s-parameter curves, resulting from the respective $\hat{\mathbf{Z}}$ for each $\varepsilon_{\text{tune}}$ are calculated within seconds, and are thus faster compared to the MWS parameter sweep. For example, for a fixed $\varepsilon_i = 2.37$ the parameter sweep of $\varepsilon_{\text{tune}}$ between $34\ldots41$ using MWS 2011 takes $t_{MWS} \approx 1\text{h}$. On the same machine, the multivariate MOR, which is implemented in MATLAB, takes $t_{\text{MOR}} \approx 25\text{min}$ to calculate $\mathbf{V}$ and to do the sweep.

SUMMARY

In this work it has been demonstrated that it is possible to increase the pickup sensitivity and to tune the design to different beam velocities, but the biggest difficulty for the realisation of this pickup design will be the dielectric losses in the material. For this reason the tunable material to use for this design must have a very low loss tangent, for instance Strontium Titanate as mentioned at the end of the second section. The classical parameter studies which require multiple simulation runs based on the original numerical model in order to characterize the various design parameters have been compared with studies based on reduced order models. A fast frequency response evaluation under consideration of material variations has been achieved. Thus, the parameter sweep required for an estimation of the tunable material range, before its optimization, can be replaced by a faster parameter sweep with the help of MOR.

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