GROUNDED COPLANAR WAVEGUIDE TRANSMISSION LINES AS PICKUPS FOR BEAM POSITION MONITORING IN PARTICLE ACCELERATORS*

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Abstract

Energy beam position monitors (EBPM) based on grounded co-planar waveguide (CPW) transmission lines have been designed for installation in the dispersive sections of the bunch compressor chicanes at the European XFEL. In combination with beam position monitors at the entrance and exit of the bunch compressor chicanes, measurements of the beam energy with single bunch resolution are feasible. The EBPM consists of transversely mounted stripline pickups in a rectangular beampipe section. The signal detection for the measurement of the phases of the pulses at each end of the pickups is based on the standard down-conversion and phase detection scheme used for the low-level RF-system. A measurement resolution within the lower micrometer range can be achieved for input signal reflections at the pickup of less than -25 dB at 3 GHz In this paper, simulation results of a novel pickup geometry utilized with CPW pickup structures and optimized transitions to perpendicular mounted coaxial connectors are presented. The simulation results exhibit small reflection coefficients with reflected signal components having less than 2% of the peak voltage signal.

INTRODUCTION

The operation of the European XFEL will require multiple special diagnostic tools to study and adjust the properties of the electron bunch. For the longitudinal properties Energy Beam Position Monitors (EBPMs) are utilized at three different locations along the European XFEL LINAC. Here the EBPM consists of two transversely mounted striplines and signal detection system, which measures the phases of the pulses emerging from both ends of the pickup in the dispersive section of a bunch compressor chicane [1]. The bunch energy can be determined from the phase differences that are directly proportional to the beam position by the formalism of the bunch compressor [2]. The principle of operation is visualized in Fig. 1 that shows a realized EBPM in FLASH [3]. It consists of two transversely mounted striplines within a rectangular beampipe section. The striplines are open coaxial transmission lines fixed with ceramic disks at both ends for mechanical support. Towards the connectors the rods are tapered. The bunches excite signals on the coaxial lines that travel to both ends. The phase difference between the measured phases on the left and right side is direct proportional to the bunch position. The measurement resolution is defined by the minimum detectable phase-difference between both pulses. The phase of the pulse is defined by the phase constant of the transmission line that is the imaginary component of the propagation constant. It represents the change in phase per meter along the path by the wave at any instant. Without any distortions on the transmission line the phase constant is directly proportional to the frequency of operation. The higher the operation frequency, the higher the phase constant and thus the phase-difference between both ends of the line. The measurement resolution is limited by the maximum operation frequency of the pickup, the limitations of the detection electronics and the length of the active sensor region which imposes the wavelength, below which the phase detection will be no longer unique [4]. The mechanical and electrical requirements for future EBPMs at the European XFEL differs significantly from the ones at FLASH. The opening of the rectangular beamline section is increased from $L = 183$ mm, $H = 8$ mm for FLASH to $L = 400$ mm, $H = 40.5$ mm for XFEL and at the same time the minimum detectable bunch charge is reduced from 1 nC for FLASH to 20 pC for XFEL. First results of planar transmission line pickups as a baseline for the XFEL EBPM monitor were presented in [3]. This paper shows a possible upgrade of the EBPM by a quasi-grounded coplanar waveguide that combines the advantages of microstrip

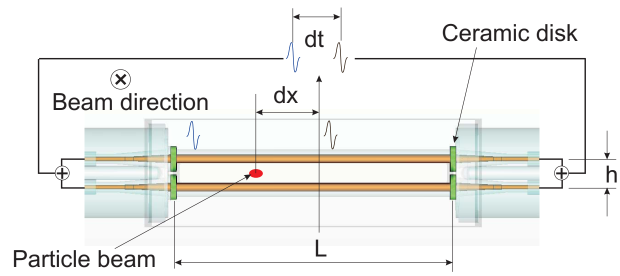

Figure 1: CAD model of the EBPM installed in the second bunch compressor at FLASH [3].

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transmission lines and coplanar waveguide structures.

PLANAR TRANSMISSION LINE PICKUP DESIGN

Due to the large dimensions of the rectangular beam pipe for the European-XFEL a mechanical stable pickup design with high sensitivity is necessary. The current solution for FLASH utilized with cylindrical rods and two ceramic disks as support create miss-match and thus reflections of the signal [3]. The reflections of the signal strongly influence the detection accuracy and need to be minimized for the upgrade of the detection scheme for the E-XFEL EBPMs introduced in [4]. In the current implementation ceramic disks at both ends of the line fixes the inner conductor to the outer one. Due to the miss-match of the line section with the discs, reflections of the induced signal are generated, which makes it not feasible to be used together with the upgraded detection scheme, since the error in the detected position scales with the reflected pickup signal. Simulations as well as measurements of non-hermetic prototypes exhibits high signal quality as well as low reflections of the planar designs [3, 5]. For the baseline design at E-XFEL, a microstrip line, as shown in Fig. 2 was utilized. The line consists of a conductor layer and a ground layer with a dielectric material in between. The electrical field is concentrated underneath the conductor strip and stray fields radiate within the substrate and air. The signal is usually coupled to a orthogonal attached coaxial line. The beam induces a signal to the stray field of the microstrip line. The thickness of the dielectric substrate is a tradeoff between the coupling to the beam and the reflection coefficient of the transition to the coaxial line. The thicker the substrate, the better the coupling to the beam, but the worse the reflection is from the microstrip to coaxial transition.

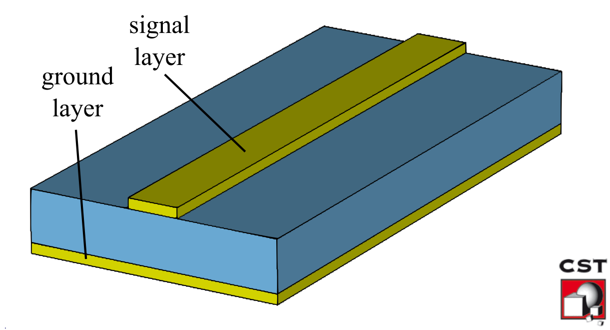

Figure 2: Model of a microstrip transmission line.

The second design, that was investigated, was a grounded coplanar waveguide (CPW) structure as shown in Fig. 3 The grounded coplanar waveguide consists of a signal layer surrounded by two ground layer on top of the substrate and a third ground layer below the dielectric substrate. The ground layer are connected to each other by vias consisting of metallic posts in order to prevent substrate waves. The necessary lateral dimension is limited to the distance of the metallic posts. Here a fraction of the electrical field is concentrated within the substrate and the rest radiates in the air. The field is concentrated in the gap between the signal layer and the ground layer. As for the microstrip transmission line, the coupling from the beam to the CPW and from the CPW to the coaxial line is a function of substrate height. The conductor with and the overall dimension of the the microstrip and the CPW transmission line as a function of substrate height is displayed in Fig. 4. It can be seen that for low substrate heights also the conductor and thus the coupling to the beam is weak. With increasing substrate height up to 3 mm the conductors for both lines rise up to about 7 mm and 5.8 mm for the microstrip and CPW line respectively. On the right side of the graph the necessary overall dimension for both line are displayed. It is remarkable that the microstrip line needs about three times more space than the CPW line. For 3 mm substrate height the overall dimension needed for the CPW line is less than 10 mm whereas the microstrip line needs about three times more space [6]. The drawback of the grounded CPW line is the more complex design compared to microstrip which is even more difficult to mount within a vacuum environment[7].

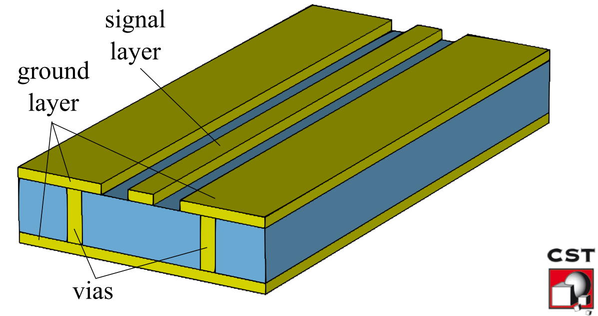

Figure 3: Model of a grounded coplanar waveguide structure.

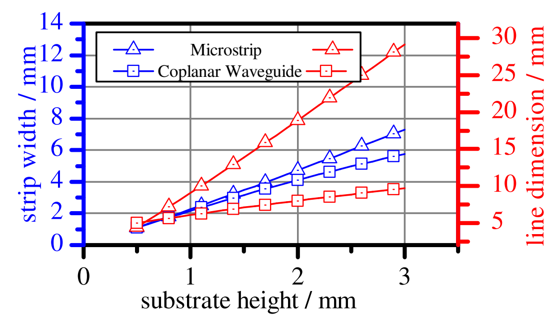

Figure 4: Conductor width and overall dimension of a microstrip and a GCPW line for a 50Ω geometry as a function of substrate height.

The microstrip transmission line approach has a large substrate dimension in beam direction. Due to the low lateral size, a grounded CPW line is investigated. To make the CPW approach applicable for usage in accelerators, the

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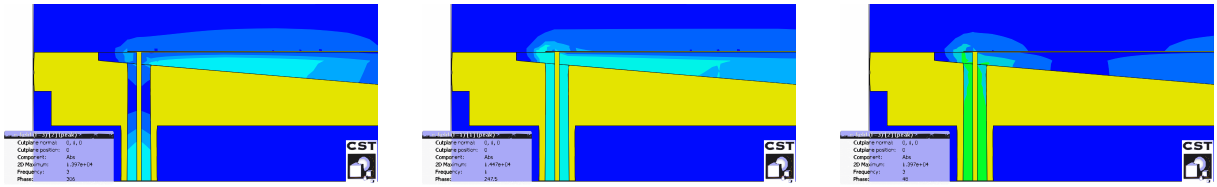

Figure 7: Field distribution versus time; left, e-field maxima travels to the taper; middle, e-field maxima at transition to coaxial line; right, e-field within the coaxial line.

CPW structure needs to be adapted to fulfill the vacuum requirements. In the proposed structure, the vias are exchanged by two metallic walls. Furthermore the metallic walls are shifted to the edge of the ground strips on the top layer as shown in Fig. 5. For maintaining the 50 Ω geometry, the gap between the line and the ground layer was increased slightly compared to a standard grounded CPW line. To match the wave impedance for the smaller line width, either the gap needs to be reduced for a constant substrate thickness or the thickness needs to be reduced for a constant gap. The matching to the transition is performed by a tapered reduction of the substrate thickness due to the parasitic effects in the transition section. Fig. 6 shows the cross section and the top view of the structure. The transition is performed by a reduction of the line from 5.75 mm down to 1.8 mm and a thickness reduction from 3 mm down to 0.8 mm. Fig. 7 exhibits the electrical field at the CPW to coaxial line transition in the cross-sectional view. In the left figure, the field is concentrated below the conductor traveling to the taper section. In the middle the e-field is concentrated at the edge of the taper to the coaxial line. It can be seen, that still a small fraction of the field radiates at the edge of the conductor line. On the right figure the field is already within the coaxial line and no backwards traveling wave is visible.

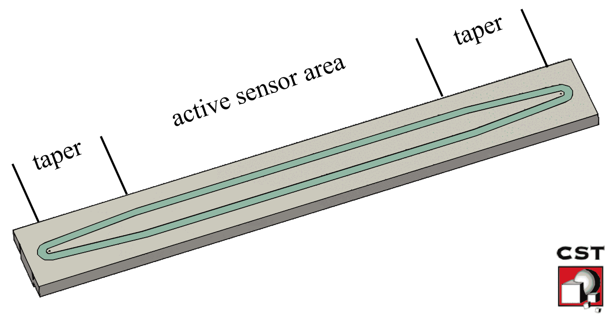

Figure 5: Simulation model of the quasi-grounded CPW structure.

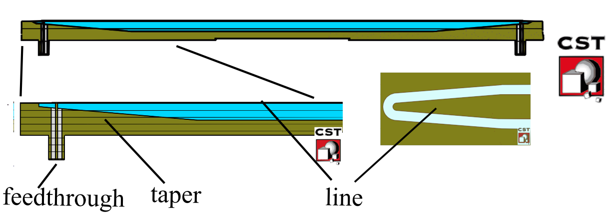

Figure 6: Modified grounded CPW line with perpendicular coaxial line transition. Upper, cross-section of the sensor structure; lower left, taper; lower right, top view.

Fig. 8 shows the simulated S-parameters of the structure.

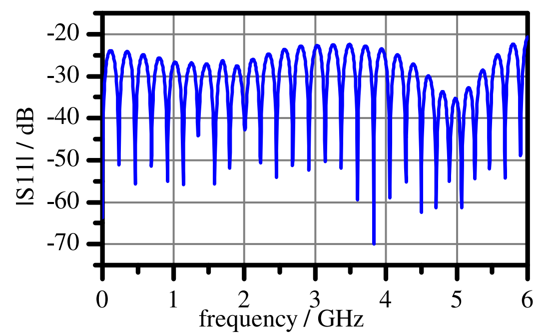

Figure 8: S-parameter results of the grounded CPW structure.

The input reflection of the transition is less than −25 dB in the frequency range from 1 GHz up to 6 GHz. The transition was adapted to the BPM structure with European-XFEL beam pipe aperture the grounded CPW is simulated with a beam excitation. The results are shown in Fig. 9. As expected, a part of the signal is reflected at the opposite end of the transmission line and travels back. The reflected pulse has a signal strength less then 2 % of the signal pulse in the case of grounded CPW structure.

In order to fabricate the structure for usage within hermetic sealed environments, a micro machined substrate cannot be used, since gaps between the substrate and ground needs to be realized to secure no air inclusions below the substrate layer. This would significantly reduce its electrical characteristic, so that the signal reflections be worse that the proposed microstrip line in [3]. In order to prevent gaps between the glass-substrate and the metal ground layer, the usage of special glass composites to be melted and filled in the hollow structures are currently under investigation. Besides the omission of gaps between the substrate and ground, also the hermeticity is secured. At the same time the mechanical stability is increased and thermal expansion would not be critical anymore.

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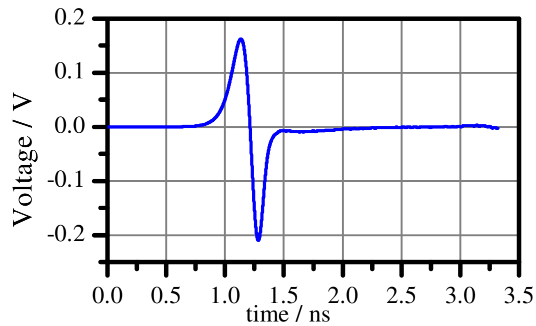

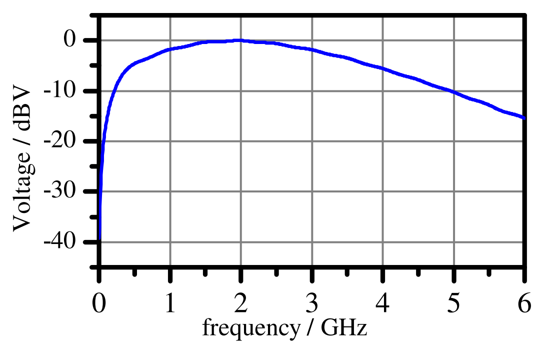

Figure 9: CST PARTICLE STUDIO simulation of the CPW pick-ups. Upper figure, voltage in time domain; Lower figure, voltage in frequency domain.

CONCLUSION & OUTLOOK

The beam position monitoring for the accelerators FLASH II and the European-XFEL uses a new detection scheme with an operation frequency of 3GHz. To reach the objected spatial resolution of less than 20 μm the detection system allows a maximum input reflection of -25 dB of the signal amplitude. In a former paper a comparison between the implemented coaxial design and a standard microstrip design represented the advantage of planar structures for beam position measurements. In order to improve the baseline design a new grounded coplanar transmission line concept was investigated. Simulation results exhibit excellent input matching lower then -25 dB over a broad frequency range from 1 GHz up to 6 GHz. For both structures the reproducibility in hermetic environment was taken into account. To verify the simulations the structure will be manufactured with vacuum flanges and characterized with S-parameters.

ACKNOWLEDGEMENT

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