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DESIGN AND DEVELOPMENT OF A NOVEL STRIPLINE FAST FARADAY CUP TO MEASURE ION BEAM PROFILE

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Abstract

Present day heavy ion accelerators use bunched ion beams of sub-nanosecond time scale for beam acceleration. In order to monitor the longitudinal beam bunch profile, Fast Faraday Cups (FFC) are employed. Owing to the advent of microstrip technology and its fabrication process, planar structures have become easier to fabricate. A novel planar design using the same is developed with a special provision for mounting edge launch connectors through a microstripline feed, followed by a microstrip to stripline transition to again a microstrip structure in the beam interaction hole. The entire structure is symmetrical and bidirectional with 50 Ω transmission lines. An experimental study on via placement around central stripline has also been conducted to not only ensure the field containment around the strip but also for bandwidth enhancement. To measure ion beam currents from 10-100 nA and a bunch width of < 1ns, device has a beam interaction hole of around 10mm. 3 dB bandwidth is measured > 6 GHz resulting in a pulse rise time of ~60 ps or less. The proposed device is also provided with a bias ring on the topmost layer of the 3 layer architecture for electron suppression. In this paper, design, fabrication and RF testing of stripline fast faraday cup is presented.

INTRODUCTION

The 15 UD Pelletron and the upcoming High Current Injector produces pulsed ion beam to be further energized by the Superconducting LINAC of IUAC. The bunch length acceptance of the superbuncher cavity of LINAC is ~1-2 ns which further reduce it to 200-500 ps. In order to determine the time and energy structure of the beam bunches, it is essential to measure the longitudinal profile and Time of Flight of the beam. By employing Fast Faraday Cups, longitudinal profile of a beam can be measured. Stripline FFCs are interceptive devices made up of a printed circuit transmission line of 50Ω or any given impedance [1] which can produce picosecond pickup pulse response when ion beam bunches strike on it. Figure 1 shows typical application of FFC device at IUAC where response times of the order of 50-60 ps or > 6 GHz bandwidth are well suited. Aim of this paper is to design such a novel stripline FFC as per IUAC requirement.

The most notable works on stripline FFC design are found in [2-3] which have used multilayer structure with stitching vias to maintain signal integrity, and bandwidth enhancement. While these devices have a small beam interaction hole and used for very high current, high energy beam species, the proposed design is provided with larger beam interaction hole to cater even for low beam currents produced at IUAC which are of the order to 10-100 nA. Extensive studies on via fencing suggested [4-7] for suppression of spurious modes in stripline geometry using ground-to-ground stitching via filled with copper / metalized rods has been extended for the present case as well.

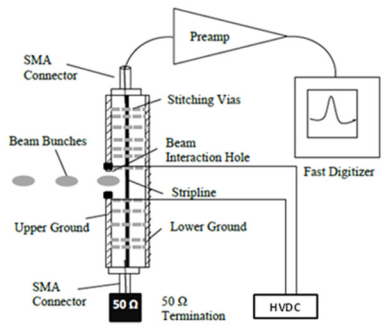

Figure 1: Beamline Test Setup.

Various sections of this paper deals with design equations and novelty implied therein. Emphasis has been given on stitching via placement and its mode suppression-cum-bandwidth extension effects. Paper is concluded by comparison of results of EM simulations done in Ansoft's HFSS with measured results obtained on VNA.

DESIGN DETAILS

The proposed configuration of stripline device is shown in Fig. 2. It is realized as a 3 layer, stacked-up structure of two planar substrates. Upper one has two rectangular notches at both edges so as to connect two SMA edge launch connectors. A beam interaction hole of the order of 10 mm diameter has been made at the center of the device for the beam sizes of the order 3-4 mm in diameter. Lower substrate has a grounded transmission line structure.

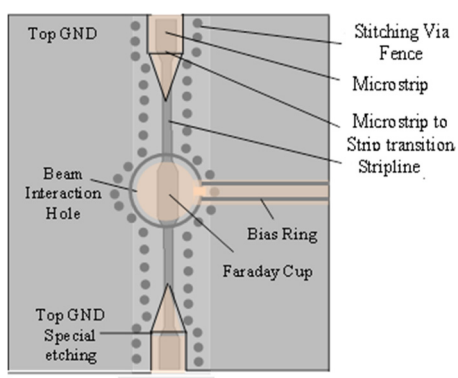

Figure 2: Proposed Stripline FFC Design.

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After the removal of notches and central cylinder, the geometry essentially becomes a microstrip based at these locations. So, we use the 50Ω microstripline design formula to calculate the width at these three locations while rest of the central trace is composed of 50Ω stripline. In order to transform the fields from microstrip-to-strip line and vice-versa, tapered transition is employed [8]. Additionally, along the tapered line, the copper pour on the upper substrate is etched in the same tapered fashion so that impedance of the line is still maintained to 50Ω.

The stitching via fence is placed on both side of central trace, shorting the top and bottom ground planes to supress leakage of unwanted modes. In order to further reduce reflections at the transition from microstrip-to-stripline, via fences are placed around the SMA connector closer than other points along the trace [3]. The part of the central trace at the beam interaction hole is called as Faraday Cup. In order to suppress the secondary electron emission, a bias ring can also be provided around the central beam interaction hole to which a negative voltage supply can be connected. To accommodate this ring on the top ground layer, a portion of copper pour is etched and bias trace is insulated from ground plane.

The substrate used is of Teflon class which is preferred for high to ultra-high vacuum conditions. All the microstrip line components are 50Ω, $\lambda_d/4$ line lengths. This is done to ensure that the phase shift experienced by the signal while traversing through the line is between -180 deg. to +180 deg.

Design Formulae

Impedance of planar stripline structure is computed using Eq. (1), (2) [1]:

$$Z_o = \frac{30\pi}{\sqrt{\varepsilon_r}} \frac{b}{W_e + 0.441b}. \tag{1}$$

$$\frac{W_e}{b} = \frac{W}{b} - \begin{cases} 0 & for \frac{W}{b} > 0.35 \\ (0.35 - W/b)^2 & for \frac{W}{b} < 0.35 \end{cases} \tag{2}$$

Where 'W_e' is the effective width of central conductor, 'W' is the physical width of central conductor and 'b' is the total height of the substrate. Similarly, impedance based geometry calculations are done for microstrip structure per Eq. (3)-(6).

If (W/H) > 1

$$\varepsilon_{eff} = \frac{\varepsilon_R + 1}{2} + \frac{\varepsilon_R - 1}{2} \left[\frac{1}{\sqrt{1 + 12\left(\frac{H}{W}\right)}} + 0.04\left(1 - \left(\frac{W}{H}\right)\right)^2 \right] \tag{3}$$

$$Z_o = \frac{60}{\sqrt{\varepsilon_{eff}}} lnH\left(8\left(\frac{H}{W}\right) + 0.25\left(\frac{W}{H}\right)\right) \tag{4}$$

If (W/H) > 1

$$\varepsilon_{eff} = \frac{\varepsilon_R + 1}{2} + \left[\frac{\varepsilon_R - 1}{2\sqrt{1 + 12\left(\frac{H}{W}\right)}} \right] \tag{5}$$

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}} \left[\frac{W}{H} + 1.393 + \frac{2}{3} ln\left(\frac{W}{H} + 1.444\right) \right]} \tag{6}$$

Figure 3 shows the basic stripline geometry while via-fences. Following considerations are taken into account while designing vias [2-6]:

- Via pitch *'p'* should be randomly varied and is kept less than λ_d $(= c/(\sqrt{\varepsilon_r} f_d))$ to prevent effective RF boundary. Typically less than $\lambda_d/8$, so as to prevent a potential difference between the ground planes leading to a parallel plate mode.
- The via fence-to-fence separation '*s*', should be a minimum 3 to 5 times the strip width.
- If via fence-to-fence separation is too great, a pseudo rectangular waveguide mode can be excited.

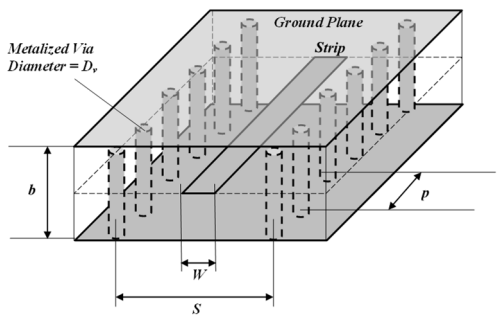

Figure 3: Stripline Structure with Via-Fence.

Mode Suppression

The study in [7] has been extended to the stripline geometry considering that both the ground planes are getting excited by the fringe fields of the central transmission line like a rectangular patch. This rectangular patch now behaves like a parallel plate type of resonant cavity with higher order modes in the absence of via-short. The higher order modes follow the Eq. (7) for determination of cut-off frequency of resulting structure:

$$f_{rmnq} = \frac{c}{2\sqrt{\varepsilon_r}} \sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W_g}\right)^2 + \left(\frac{q}{b}\right)^2} \tag{7}$$

Where L, W_g, and b represents the length, width and height of the substrate respectively. Eq. (7) can be simplified further due to $b << \lambda_d$ and can be re-written as:

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$$f_{rmn0} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W_g}\right)^2} \quad (8)$$

In the Eq. (8), different values of 'm' and 'n' decide the spurious mode that may propagate inside the geometry. Upon the HFSS simulation study for the cases shown in Fig. 4, it is seen that in the absence of via, 3 dB bandwidth is highly restricted to a very low value. However, with the introduction of stitching vias and subsequent variation in the via-fence spacing, the spurious low frequency resonant modes are progressively shifted to higher frequencies thereby increasing the usable 3 dB bandwidth of the resulting device.

Figure 5 (top) shows the plot of Transmission Coefficient (S21) with frequency with and without via whereas in Fig. 5 (bottom), S21 is plotted against frequency for different values of via-fence spacing 's' displaying the bandwidth enhancement with reducing value of 's'.

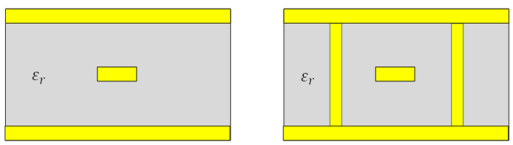


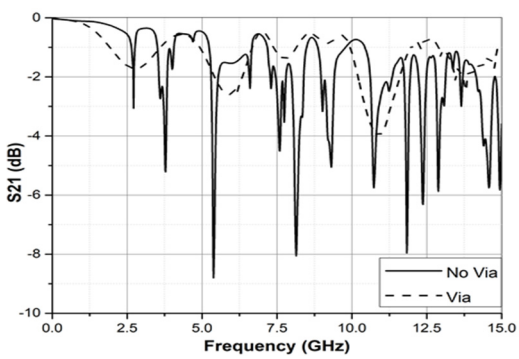
Figure 4: HFSS Design Model for Striplines.

HFSS simulation parameters for the above study are as follows: L = 60.8 mm, W_g = 45 mm, b = 1.6 mm and ε_r = 3.55.

Table 1 shows the list of frequencies as per respective mode for different values of m and n which are obtained from Eq. (8) and the HFSS simulation.

Table 1: Cavity Mode Resonant Frequencies For Stripline Structure Without Via

Mode	Eq. (8)	HFSS results
f_{r110}	2.2 GHz	2.66 GHz
f_{r210}	3.16 GHz	3.55 GHz
f_{r120}	3.73 GHz	3.75 GHz
f_{r310}	4.3 GHz	4.02 GHz
f_{r130}	5.29 GHz	5.365 GHz



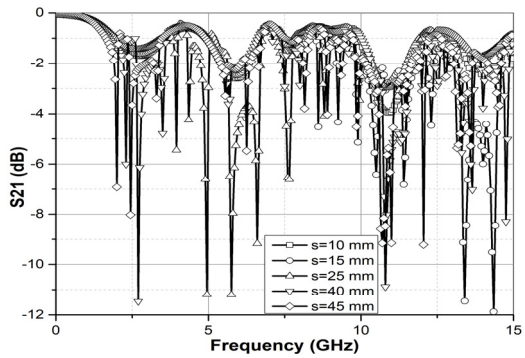


Figure 5: S21 vs Freq. with and without via-fence (top), parametric study with variable via-fence spacing (bottom).

EXPERIMENTAL RESULTS

Design parameters for the proposed design are summarized in Table 2. These are decided after optimized simulation in HFSS. Roger's RO4003C substrate has been used and simulation is performed in driven terminal mode with lumped port and λ_d /4 sized radiation box. The solution frequency of ~10 GHz is used and via pitch is restricted to be $\leq \lambda_d/8$. Figure 6 shows the two types of devices were simulated, i.e. one with bias ring and another without bias ring. Based on the simulations, fabrication is done. Since device is to be made vacuum compatible, two stitched substrates are further sealed by providing a copper sealant at the edges to avoid any air-gap.

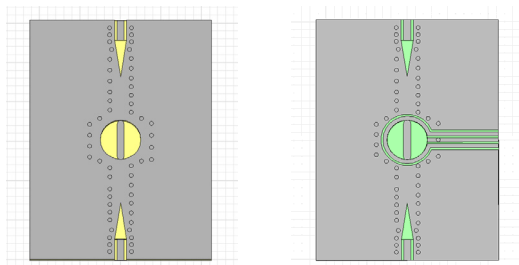


Figure 6: Proposed Stripline FFC design in HFSS.

Table 2: Stripline FFC EM Design Parameters

Parameter	Value
Substrate	RO4003C
Substrate 1 Dimension *(w × l × h)*	45 mm × 60.8 mm × 0.8 mm
Substrate 2 Dimension *(w × l × h)*	45 mm × 60.8 mm × 0.8 mm
Dielectric constant ε_r	3.55
Strip Width	0.7753 mm [50Ω]
Microstrip width	1.804 mm [50Ω]
Via Size (dia.)	1 mm
Via Pitch	≤ 1 mm
Via fence spacing	5.3 mm
Beam Interaction Hole (dia.)	10 mm (upper substrate)

Further, Fig. 7 (top) shows the finished device which is tested on a 6 GHz VNA which is a ZVL series device from Rohde & Schwarz. Figure 7 (bottom) shows the

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device under test and Fig. 8 shows the comparison of simulation and measured results.

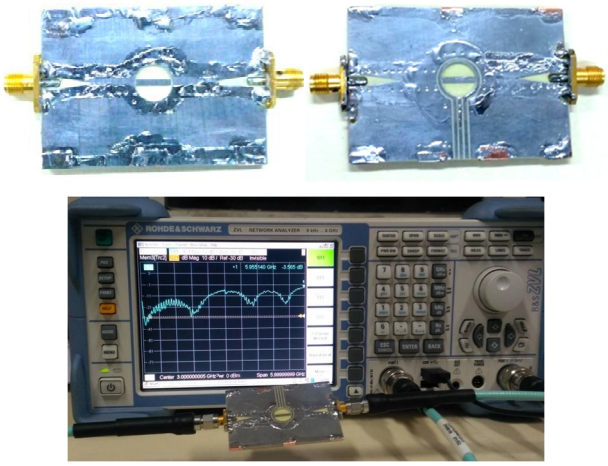

Figure 7: Fabricated Stripline FFC without and with bias ring (top), Measurement Setup (bottom).

The fabricated stripline devices are observed to be useful for a bandwidth of ~ 6 GHz (due to VNA bandwidth limitation) as shown in Fig. 8 where it maintains |S21| < ~3 dB thereby making the device useful to handle beam bunches with a rise time of <~60 ps. However, simulations have shown the bandwidth > 10 GHz.

Some abrupt discontinuities are observed due to co-placement of bias ring which is absent in design without bias.

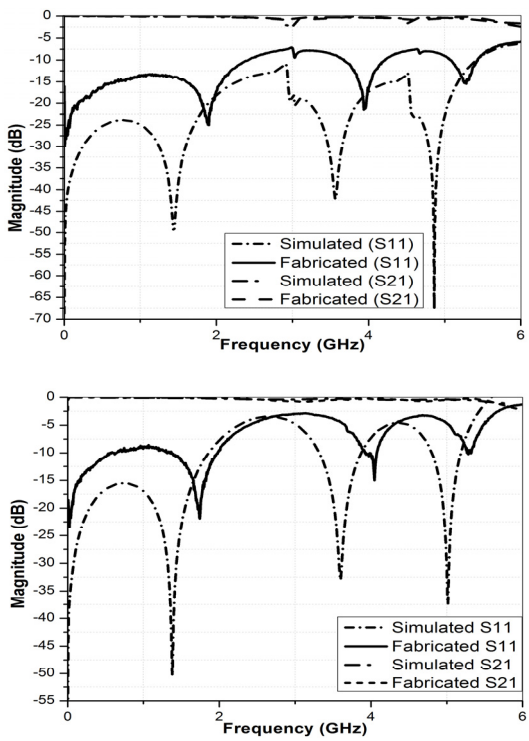

Figure 8: Comparison of Simulated and Measured results FFC with bias ring (top), FFC without bias ring (bottom).

CONCLUSION

Proposed devices are found suitable to measure the ion beam bunch widths of the order of 200 ps to 1 ns out of the IUAC Pelletron, HCI and Linear accelerator. The devices are ready to be mounted on the beam line to perform the measurement.

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