Design and Construction of Planar mm-Wave Accelerating Cavity Structures

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Feasibility studies on the planar millimeter-wave cavity structures have been made. The structures could be used for linear accelerators, free electron lasers, mm-wave amplifiers, or mm-wave undulators. The cavity structures are intended to be manufactured by using DXL (deep x-ray lithography) microfabrication technology. The frequency of operation can be about 30GHz to 300GHz. For most applications, a complete structure consists of two identical planar half structures put together face-to-face. Construction and properties of the constant gradient structures that have been investigated so far will be discussed. These cavity structures have been designed for 120GHz $2\pi/3$ -mode operation.

I. INTRODUCTION

Previously, a 50MeV compact microlinac system using micromachined planar mm-wave cavity structures was described.¹ Use of an rf gun, quadrupole magnet, and microwave undulator in the system was discussed. An accelerating field gradient of 10MeV/m was assumed in the 120GHz cavity structure. The planar mm-wave cavity structure can be used to build compact machines such as linear accelerators, free-electron lasers (FELs), wigglers and undulators.^{1,2,3} Integration of the electron guns, rf power amplifiers, magnets, and the cavities in a single wafer fully utilizes the DXL in mass-producible, microcavity structure development.

Accelerating cavity structures for mm-wave frequencies require precision machining to achieve tolerances less than a micron. If circular cylindrical cavity structures are used for mm-wave operation, meeting these tight tolerances with conventional machining can be very expensive. Fortunately, planar mm-wave cavity structures can be built inexpensively by using DXL or LIGA micromachining. The required precision channels and various indentations in a metallic substrate can be made in two symmetric planar structures. These two pieces are then combined to form a closed resonant cavity. Since the process can deliver great accuracy—tolerances of about 25-125 angstroms⁴—the precision required for the mm-wave accelerator cavity structures can be achieved. The structure may be built without requiring tuning mechanisms for the individual cavities. In the following, the accelerating cavity structures, con-

struction, input/output couplers, and other applications will be discussed.

II. STRUCTURES AND CONSTRUCTION

A planar constant impedance accelerating cavity structure and its linac application have been investigated.^{5,6} For a constant impedance planar structure, the double-periodic structures with confluence in the π -mode designs were considered.⁷ The π -mode operation in these structures can give high shunt impedance and group velocity and low sensitivity on dimensional errors. Post structures may be used to design either a constant impedance or a constant gradient structure. The post designs are also discussed.² The control of cell-to-cell coupling in the side-coupled or post structures can be made to realize the constant gradient planar structures.

The constant gradient structure has uniform power dissipation and higher shunt impedance, and is less sensitive to frequency deviations and beam break-up when compared to the constant impedance structure.⁸ The one limiting factor in the micromachining process is that the planar structure has to have uniform indentations on a planar wafer. Using microfabrication technology, it is more difficult to realize a constant gradient structure than a constant impedance structure. Changing the group velocity along the structure while keeping the gap and cell depth dimensions constant is difficult.

Since the structure needs to be manufactured on a planar wafer, adjusting the cell width and length with a constant depth within the structure is necessary. A constant gradient structure can be realized with a cut in the

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iris between the adjacent cavity cells along the beam axis in each half structure. Figure 1 shows the constant gradient structure with cuts in the irises. The irises between the cells have vertical cuts with a controlled width along the axis. The cutwidth is greatest at the input side and becomes smaller toward the output.

Fig. 1. Double-sided constant gradient cavity structure. a) longitudinal, b) transverse cut, c) top view.

A 1.5m electron linear accelerator system will require joining twenty 7.5cm-long structures end to end. The rf design requires vertical and horizontal stacking of DXL substrates. In order to achieve efficient coupling between fields and electrons, all structural dimensions must be controlled with a 0.1% accuracy. The initial structures will be vertically stacked using three techniques: optical fibers in silicon v-grooves, fibers in electroplated rectangular grooves, and DXL-generated pegs in square holes. The first technique has achieved the required accuracy but involves an extra masking step. A planar cavity and DXL mask have been created to demonstrate and evaluate the other two techniques. The mask has features to evaluate the minimum electroplated cavity radius. Horizontal stacking has been achieved with optical fibers in silicon v-grooves and 2cm-long structures have been joined end to end. This alignment method using fibers in the rectangular grooves, which was developed for a micromachined electron microscope,⁹ is shown in Figure 2.

Fig. 2. Joining double-sided planar cavity structures using glass fiber sections

Other methods, such as using the conductor cavities on the silicone substrate and using a sacrificial layer to form a completely joined structure, are also being studied. Presently, prototype cavity structures are being fabricated using the DXL technique with the glass-fiber spacers.

III. SIMULATION

Using the finite-difference, time-domain solver MAFIA codes,¹⁰ the structure was simulated to find the resonant mode frequencies, electric and magnetic field distribution, shunt impedance, etc. The cell shape in the x-z plane can be optimized for maximum performance. It was found that the structure with rounded corners in the cell and in the irises showed near-optimum properties. Figure 3 shows the 3-cell unit structure for the simulation. For unit structures with various cutwidths, the group velocity was found.

Fig. 3. 3-cell unit structure for computer simulation

A $2\pi/3$ traveling wave mode was chosen as the accelerating mode since the shunt impedance of the mode is near maximum among all modes. For a 15% leftover power at the output of a 7cm-long accelerating structure, the average attenuation $\alpha=13.6\text{Np/m}$. The required group velocity normalized to the speed of light along the structure is in the range of 0.94 to 0.14. It has been found that, for minimum coupling, $a=0.5\text{mm}$, $b=2.2\text{mm}$, $g=0.633\text{mm}$, and $t=0.2\text{mm}$ can be used. The number of cells is 84 and the shunt impedance is around $300\text{M}\Omega/\text{m}$. The effective aperture size can be greater than the small

aperture height, since the vertical cuts are made in most irises. The normalized group velocity, v_g/c , vs. the cutwidth, s , with an aperture height of $a=0.5\text{mm}$ is shown in Figure 4.

Fig. 4. Group velocity v_g vs. the cutwidth s with an aperture height of $a=0.5\text{mm}$.

Figure 5 shows the cutwidth s of a 120GHz structure along the z -axis. The cavity Q-factor becomes higher and the shunt impedance ($s > 0.1\text{mm}$) becomes lower at greater cutwidths.

Fig. 5. Cutwidth s of a 120GHz structure along z -axis.

V. INPUT/OUTPUT COUPLERS

The accelerating structures must be fed by an external rf power source. The cavity structure is fed through a rectangular waveguide which is a natural choice for a DXL-processed planar structure. The rectangular waveguide connects to the coupling cell, which requires impedance matched to the periodic structure. The imped-

ance matching structure in a coupler for high power operation needs high voltage capability and DXL compatibility.

The matching can be made by using either reactive irises or reactive stubs; the irises and the stubs can be either inductive or capacitive. The inductive irises have an indentation somewhere between the top and the bottom surfaces of the half structure, and the capacitive irises can have full height with smaller gap in between. A case with inductive irises has been computer-simulated using MAFIA codes. Figure 6 shows the inductive input/output coupler design used for the planar cavity structure. The scattering parameters, S_{11} and S_{21} , of a seven-cell structure are shown in Figure 7. A time instantaneous electric field plot of the $2\pi/3$ traveling wave is shown in Figure 8.

Fig. 6. Bottom half of input/output couplers used in the simulation for a planar cavity structure.

VI. RF GUN STRUCTURE

The next generation of linear collider and short wavelength free-electron lasers imposes stringent requirements on the quality of the electron beam. The rf photocathode source plays a key role in obtaining small emittance beams with ultra-high brightness suitable for these applications. At the PAC95 conference, MIT researchers working on a 15GHz rf photocathode gun reported encouraging results using high frequency rf gun structures for generation of low emittance and high brightness beams. At Argonne, we have started a feasibility study for a 30GHz rf photocathode source based on a double-sided planar DXL structure. Recent results on DXL exposures presented by Guckel's group at the University of Wisconsin indicate that 1-cm-deep x-ray exposure is possible.

Fig. 7. Computed scattering parameters of the inductive coupler, (a) S_{11} , (b) S_{21}

Fig. 8. Time instantaneous field plot of the $2\pi/3$ traveling wave

The rf gun used for the feasibility study is a 30GHz 3-1/2-cell side-coupled structure operated in π -mode.¹¹

Although there are many technical difficulties associated with high-frequency rf gun structures, a 30GHz photocathode rf gun allows us to reach very high gradient in excess of 500 MV/m. This drastically reduces the effects of space-charge forces and allows high-brightness beam. The gun is designed to produce electron beams with energies up to 6 MeV. The rf power is fed from a single waveguide which couples power directly to cells 2 and 3. MAFIA numerical codes, including particle-in-cell simulations, were used to model the 30GHz rf gun. The initial simulation results indicate that the beam rms emittance is between 3 and 7π mm-mrad depending on the initial rf phase. Figure 9 shows the longitudinal electric field distribution in the 30GHz side-coupled planar rf structure. A 15GHz 3-1/2-cell scale model was fabricated for cold model rf measurements. The chosen photocathode material is copper with a cathode quantum efficiency of 0.01%.

Fig. 9. Double-sided planar side-coupled 30GHz cavity structure for rf gun and the electric field

VII. DISCUSSION

The constant impedance structure is simple and easier to fabricate but is not the best for accelerator applications. Most heating occurs at the input of the structure, and this can limit the high power rf operation of the structure. In order to have higher shunt impedance, the irises between the cells must be thin (say $< 0.1\lambda$). Thus, heating at the iris center limits the maximum input power. Heat loading in a cell of a constant impedance structure and a constant gradient structure was considered.¹² The constant gradient structure is especially useful for this type of microstructure operating at a mm-wave frequency, because heat removal is vital. Successful heat removal and uniform heat loading throughout the structure are important for optimum performance of the mm-wave accelerating structure.

The construction of constant gradient mm-wave accelerating cavity structures has been described. The cavity structure and the input/output coupling structures have been computer designed. Using a pair of half struc-

tures in parallel, a precision alignment is critical and is thought to be possible. With future development of DXL, the cavity design can be practical for any frequency in the mm-wave range.

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