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Millimeter-Wave Structures and Drivers for Future Linear Colliders

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Abstract

There is a growing interest in the development of very high gradient (≥ 1 GeV/meter) accelerating structures and millimeter-wave power sources. The need for very high gradient structures to be operated in W-band or at higher frequencies poses great technical challenges and demands innovation in rf science and technology to reach this goal. Requirements for microstructure fabrication and power sources based on deep x-ray lithography techniques are examined.

1 INTRODUCTION

The highest energy linear collider today is the Stanford Linear Collider (SLC) that operates at 0.05 TeV [1]. It is a wide open question whether a 5-TeV center-of-mass energy machine can be built. If such a machine can be designed with current rf technology, it would be a few hundreds of kilometers long [2]. A potentially viable alternative to longer machines is a high gradient accelerator. A high gradient acceleration of 1 GeV/m or more is sufficient to build a 5-TeV collider that could fit on the existing Stanford Linear Accelerator Center (SLAC) site. In this paper we describe a new fabrication technique for microstructures and microwave power sources that might be fruitful for the machines of the future.

2 HIGH GRADIENT

The energies of most interest for high-energy physics have reached the multi-TeV level. Linear colliders offer the only possibility to access this energy regime with $e+e-$ collisions. Practical limitations on the size and cost of linear colliders can only be overcome if the acceleration per unit length is significantly increased in metallic structures to an order of 1 GeV/m. Due to constraints of *trapping*, *breakdown*, and *pulse heating* [3], scaling of the accelerating gradient shows that high gradient requires short wavelength. The scaling for the accelerating structures determines the essential considerations for the rf sources. For copper structures optimised for [R/Q], the scaling for wall quality factor, $Q \propto f^{1/2}$ implies a Q of 2500 at W-band and a field decay time of ~10 ns. Achieving this quality factor at W-band is not straightforward, as the surface finish becomes an issue. The more serious issue is the fabrication tolerances due to random cell-to-cell frequency errors. This implies a fabrication tolerance at the level of 2 μm or less for a W-band structure operating within 95% of optimal no-load gradient. Another issue regarding short wavelength structures is the effect of wakefields. It has been demonstrated that wakefields can be dealt with in a constructive manner, making use of the structure itself as a beam position monitor, and permitting, in principle, precision structure alignment. In the next section, we attempt to address some of these issues by employing microfabrication techniques.

3 MICROSTRUCTURES

Basic Concept

The basic elements of a mm-wave accelerating structure are shown in Fig. 1. Because the deep x-ray lithography (DXRL) structure is fabricated using wafer technology, the rf structure is a series of rectangular cavities. The features are machined on wafers by the technique described in the next section. The nominal dimensions of a single cavity are on the order of a mm or less with 0.1% machining precision. The two wafers are aligned over one another using alignment and bonding techniques developed at the University of Illinois-Chicago [4] for micromachined electron microscopes. Meter-long structures are envisioned by longitudinally staggering the top and bottom wafers to bridge across standard die sizes. The electron beam is confined to the central region of the structure either by the micromachined magnets or by rf phase focusing.

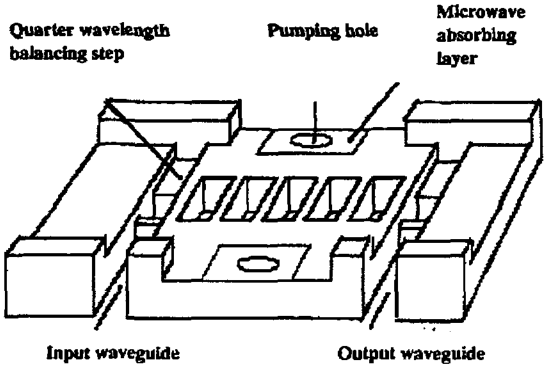

Figure 1. Muffin-tin accelerator structure.

Fabrication of Structure

Traditional mechanical machining and finishing methods will not yield 2- to 3-μm tolerances required for these structures. In fact, only lithography/chemical etching

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systems could approach the tolerances desired. The DXRL technique based on the LIGA (the German acronym for lithographe, galvanoformung, und abformung) process was used to fabricate a 66-cell, 91-GHz constant gradient structure. A basic LIGA process is shown in Fig. 2.

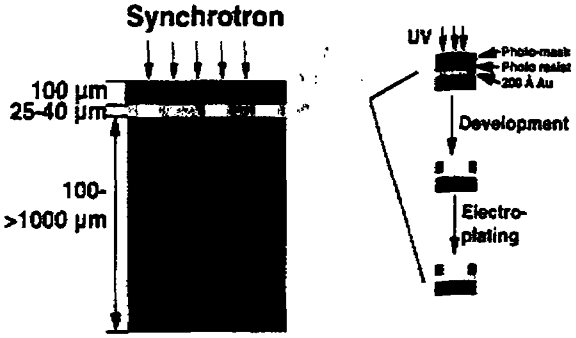

Figure 2: Basic LIGA process.

DXRL with high-energy synchrotron radiation allows resists up to 1 cm thick to be fabricated with submicron accuracy. An optical lithography mask was used to create a high-contrast x-ray projection mask, which was then exposed with a soft x-ray (1 GeV) to produce a high-accuracy DXRL mask. Poly-methylmethacrylate (PMMA) 1 mm thick was attached to a diamond-finished copper substrate for exposure. To promote better adhesion of the PMMA to the surface of the copper substrate, a 1-µm-thick Ti coating was deposited. After exposure with hard x-rays, the sample was developed. After developing the microstructure, copper was electroplated to the positive resist, and the surface was diamond finished. The final electroplated structure for a 91-GHz constant gradient structure is shown in Fig. 3. The dimensions of a single cell are 2.23 mm by 0.98 mm and each cell is separated by 0.2 mm.

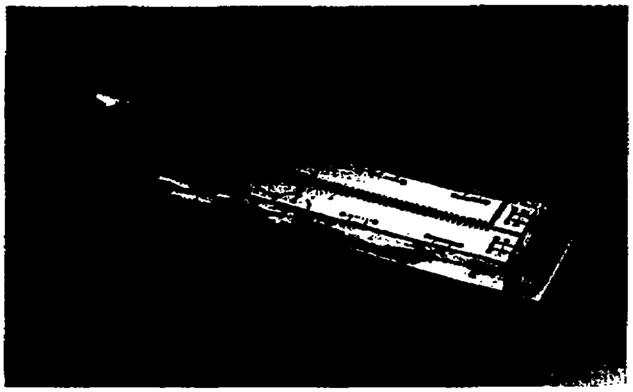

Figure 3. 91-GHz constant gradient structure.

3 POWER SOURCE

Microwave amplifiers capable of substantial power at mm-wavelength, such as travelling wave tubes (TWTs) or gyrokystrons, are scarce and very expensive. These sources employ a single, powerful electron beam that must be confined to a very small cross section or spun to very high rotational energy requiring high magnetic fields as well as very precise electron optics. The LIGA process that is used to fabricate the accelerating structure is well suited to fabricate planar structures, usable as interaction circuits of klystrons or coupled-cavity TWTs. Cavities and slow wave structures of millimeter-size dimensions can be fabricated with tolerances of a few microns and finishes of 100-2000 angstroms. A LIGA-constructed planar rf structure is the cornerstone of the module scheme for obtaining power at W-band or even at higher frequencies. It is incorporated into a 4x10 inch module consisting of four klystrons, each producing 125 kW, at a beam voltage of 120 kV and a beam current of 2.5 A [4]. Modules can be stacked and powered by the same modulator, and outputs combined for a module total of 0.5 MW. The detailed parameters of individual klystrons can be found in reference [5].

4 CONCLUSIONS

Deep-etched x-ray lithography based on the LIGA process offers a potential feasible alternative technology to the many challenges for the future of high-gradient mm-wave linear colliders. The initial R&D at Argonne National Laboratory has demonstrated the feasibility of this technique for accelerator applications [6]. It is not hard to imagine that the next generation of accelerator structures and power tube development will occur at W-band.

5 ACKNOWLEGEMENTS

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