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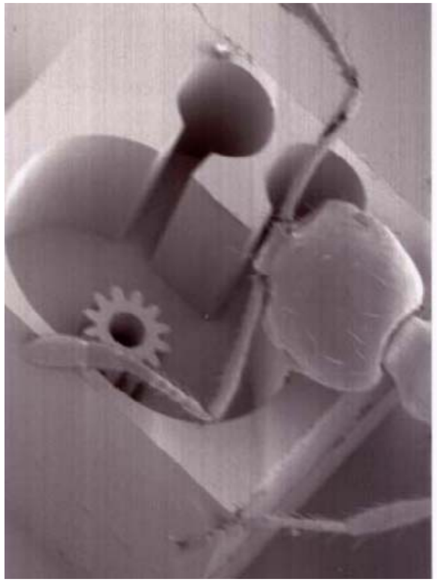
X-ray-based Microfabrication Techniques for Accelerators



A. Nassiri and R. L. Kustom

Accelerator Systems Division

X-Band Structures and Beam Dynamics Workshop

The Cockcroft Institute, UK

1-4 December, 2008

Outline

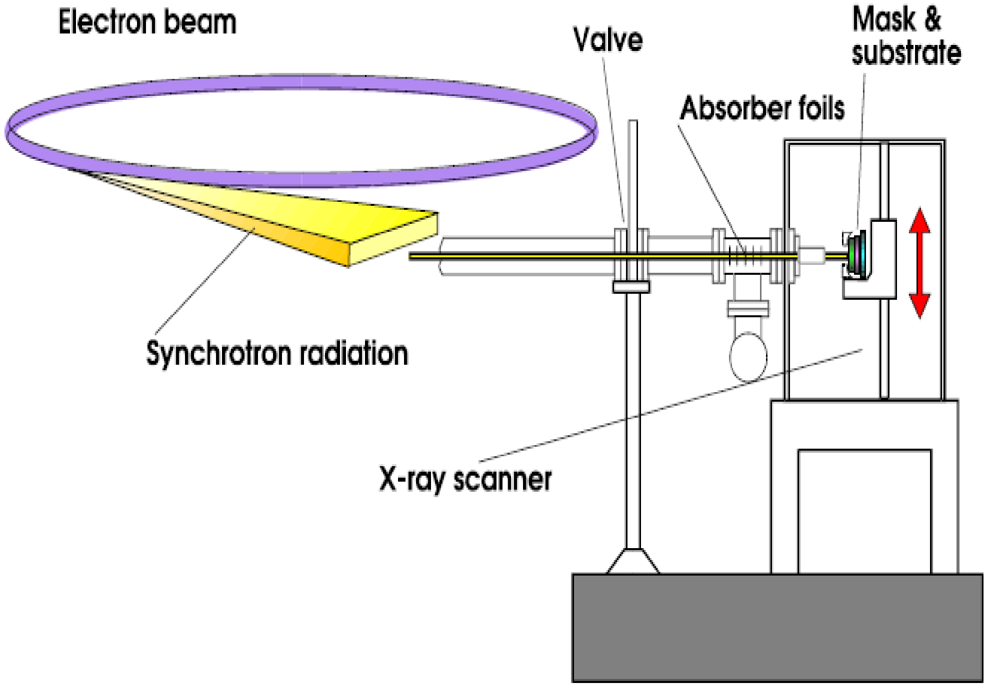
- DXRL,LIGA
- ANL work - history
- Planar structures
- Possible LIGA for CLIC
- Summary

What is LIGA?

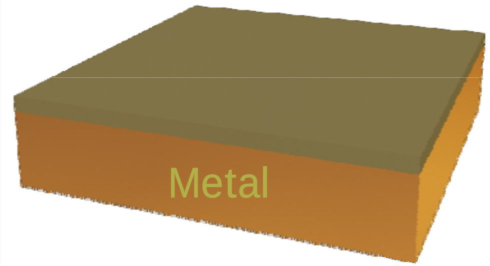
- **LIGA is a process in IC fabrication which involves lithography, electroplating, and molding on a given substrate. (Lithographie, Galvanoformung und Abformug)**
- **LIGA fabricates High Aspect Ratio Structures (HARMS).**
- **The ratio between the height and the lateral size is the aspect ratio (e.g. 100:1)**

Characteristics of LIGA

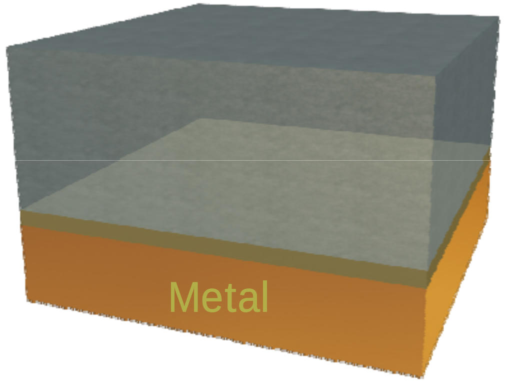
- **Any lateral shape is possible.**
- **Smallest lateral size is 0.2 μm.**
- **Structural height is about 5 mm.**
- **Aspect ratios can range up to 500.**
- **Surface roughness is small (~30 nm).**
- **Materials other than Si can be used.**



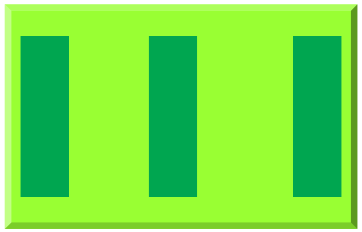
A Simplified DXRL Process



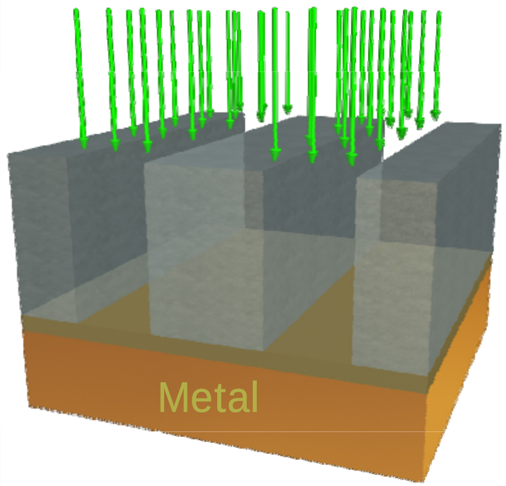
Prepare Substrate



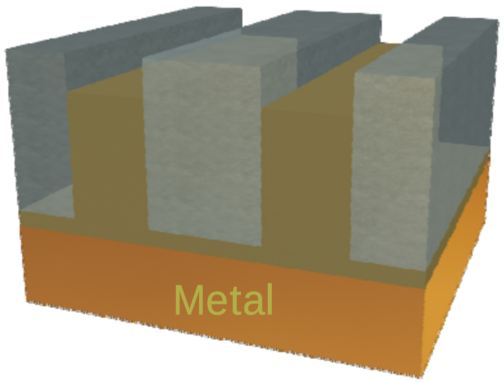
Apply PMMA*



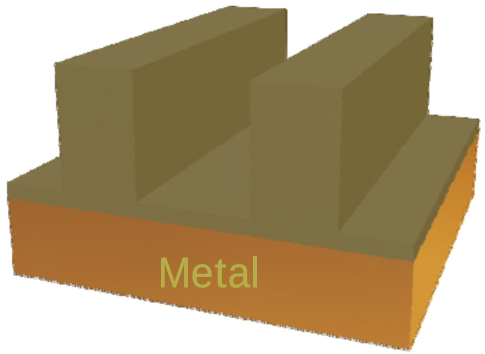
X-ray mask



Expose and Develop PMMA



Electroplate



Remove PMMA

*poly-methylmethacrylate

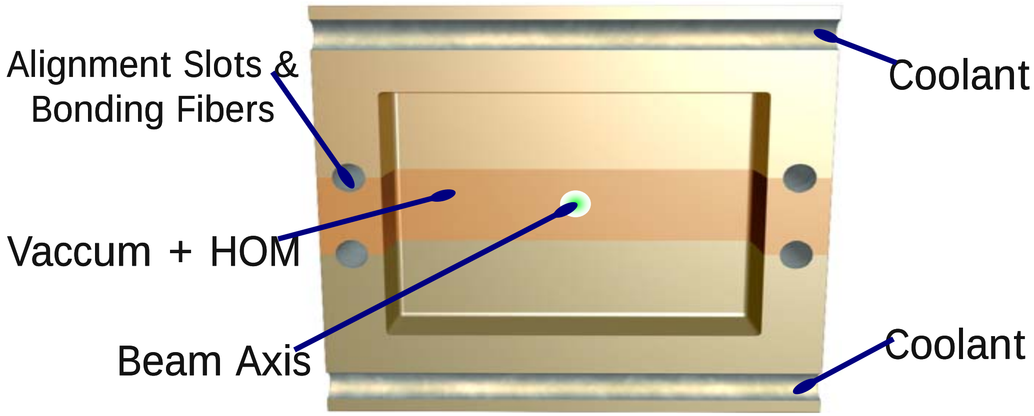
ANL Work - History

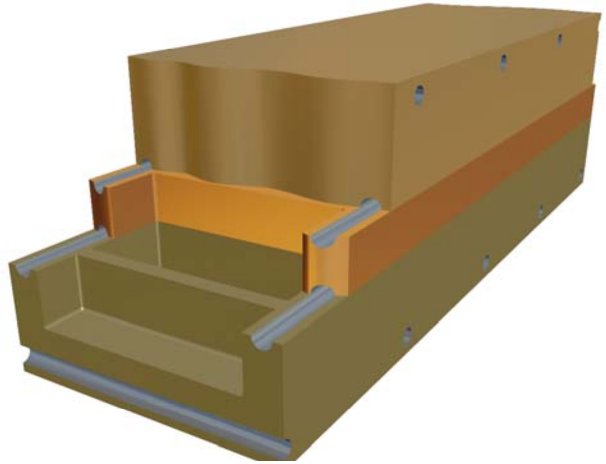
- **120-240 GHz Linac development using deep x-ray lithography (DXRL) techniques (LIGA) in 1991**
- **Developed TW planar –linac parameters in collaboration with Heino Henke of TUB in 1992**
- **Successfully built several 2π/3 structures in frequency range of 108-240 GHz using DXL techniques.**
  - **Demonstrated high precision and general fabrication techniques in collaboration with Allen Feinerman (UIC).**

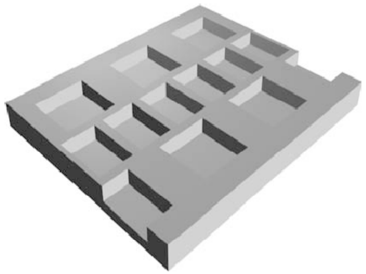
ANL Work – History (2)

- **George Caryotakis of SLAC developed a W-band micro-fabricated klystron with cavities based on our LIGA design in 1997.**
- **Studies on integration of components, multi-beam klystron, WG, circulators, etc., onto a single substrate continued until 1990 when funding ceased.**

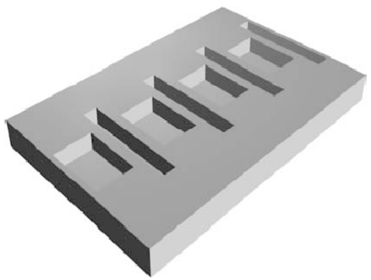
3-D Conceptual Planar Structure

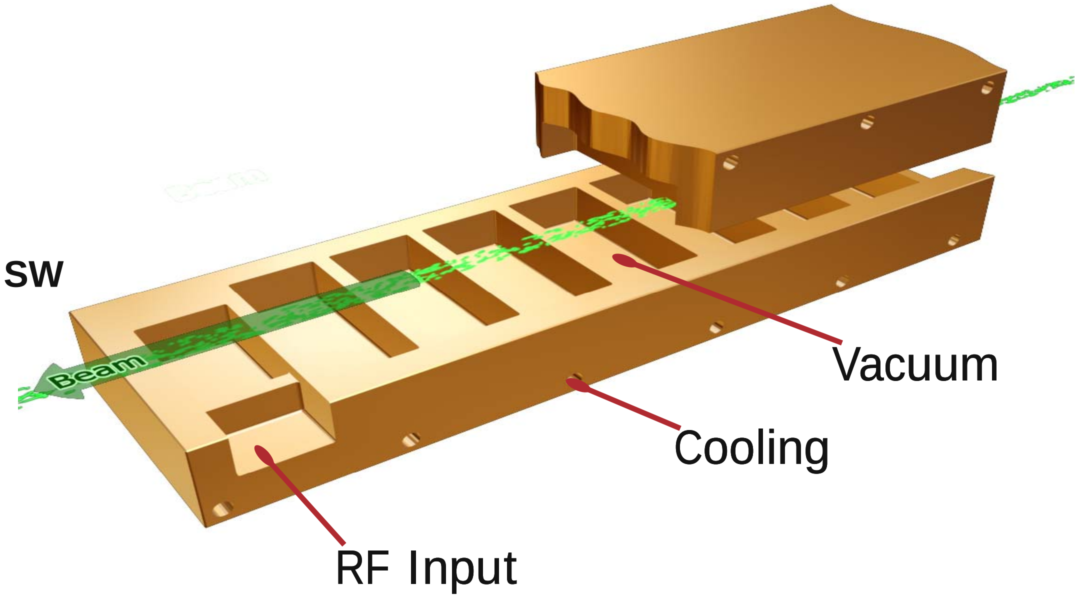






Lower half of a Side-coupled planar SW Structure

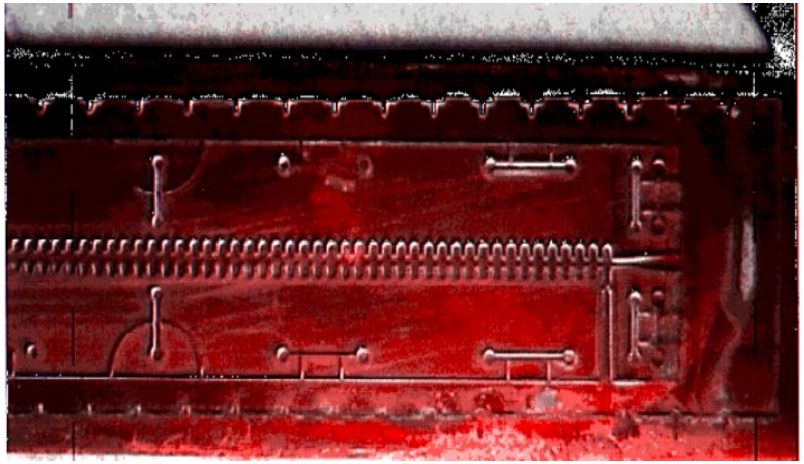


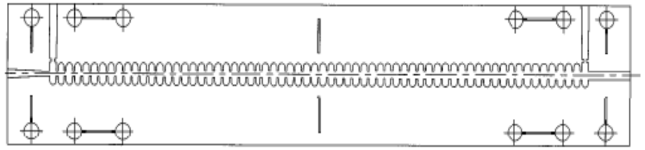


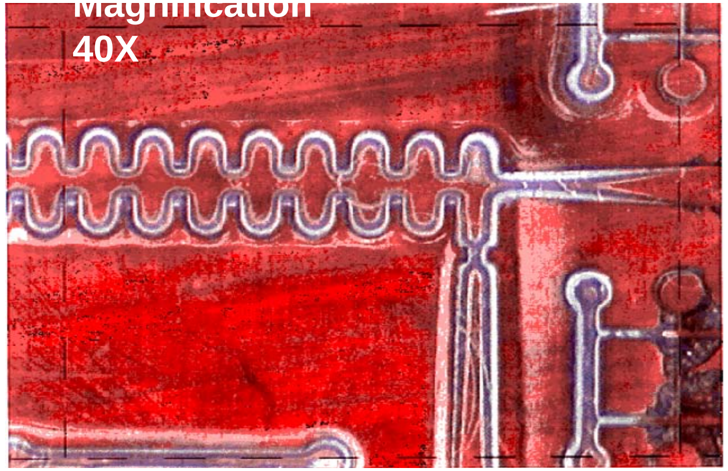
Lower half of an on-axis planar SW structure

PMMA Masks with DXRL: 94 GHz CG [1]

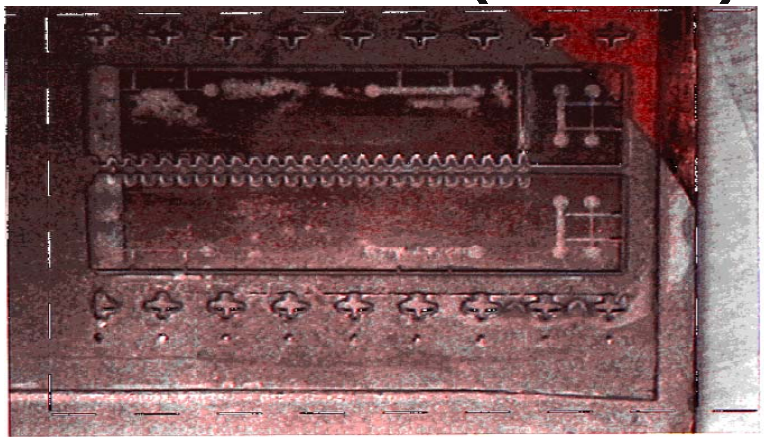
- **Long structure (66 cells)**

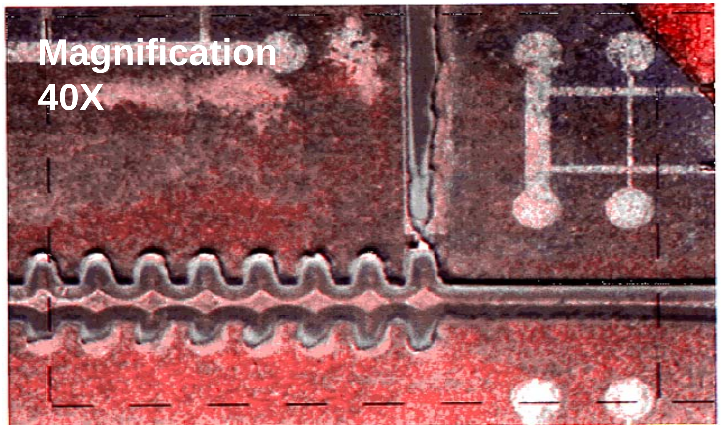






- **Short structure (30 cells)**

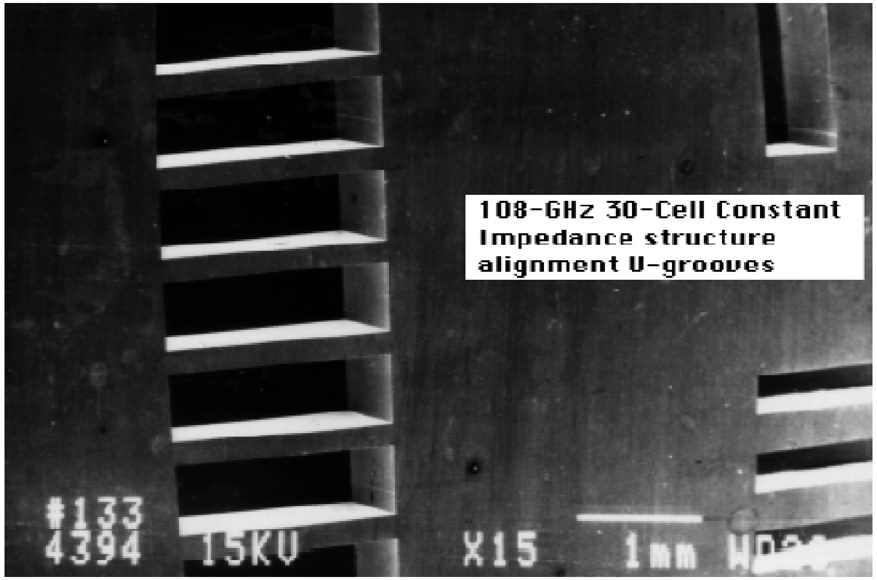




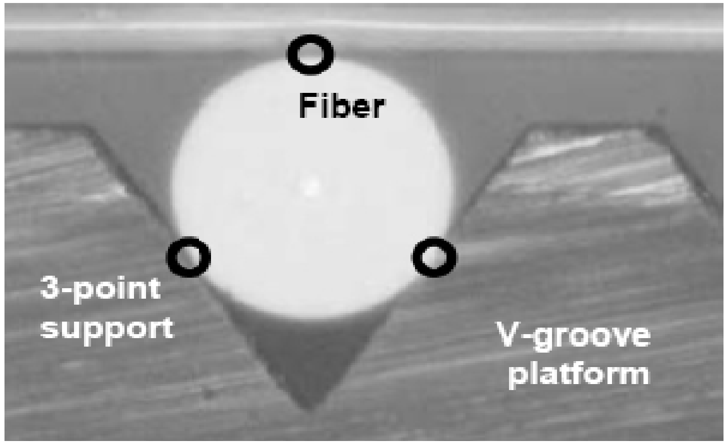
[1] J. Song, at al., Proc. Particle Accel Conf., Vancouver, B.C., Canada, 1997

CI cavity[1]

- High aspect ratio
- Surface roughness <50 nm
- High accuracy < 1 μm



SEM image of 108-GHz CI structure

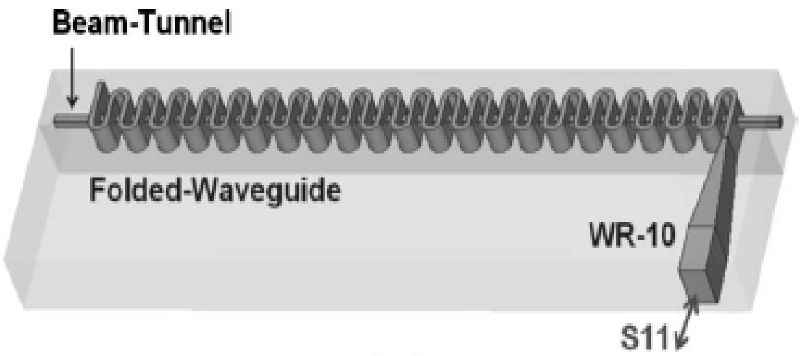


Frequency	f	108 GHz
Shunt impedance	R	312 MΩ/m
Quality factor	Q	2160
Operating mode	TW	$2\pi/3$
Group velocity	v_g	0.043 C
Attenuation factor	α	13.5 m^{-1}
Accelerating gradient	E	100 MV/m
Peak power	P	30 kW

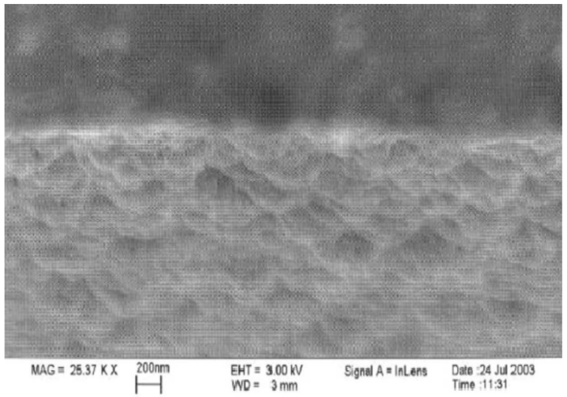
[1] A. Nassiri, at al., Proc. Int. Electron Devices Meeting, Washington, DC, December 1993

RF Components Development Using DXRL

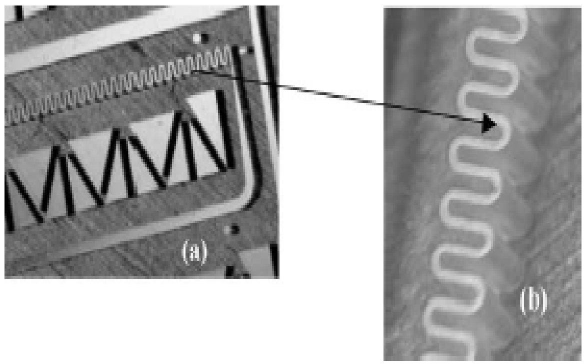
■ Folded Wave Guide TWT Sources for THz Radiation[1]

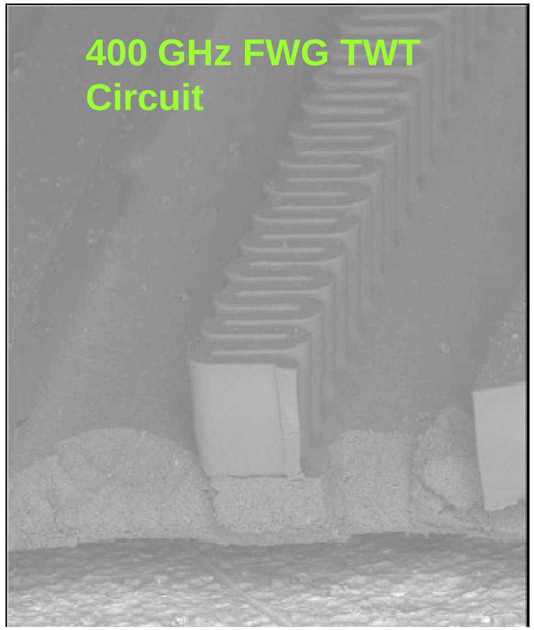


Quantity	Value
L_{tot} (cm)	1.01
L_{wg} (cm)	0.055
Number of folded waveguide cavities	154
Approximate time to complete one complete path, t_p (ns)	0.19
Total simulation time t_{tot} (ns)	1.71
Average number of path periods, n_{tp}	9



SEM image of the edge of a LIGA-produced FWG TWT circuit. Surface roughness is less than 1 µm



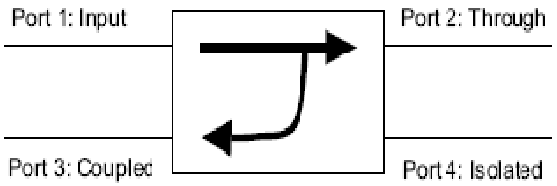


HAR mold for cu electroplating with a 250-µm high wall and a 100-µm circuit pitch

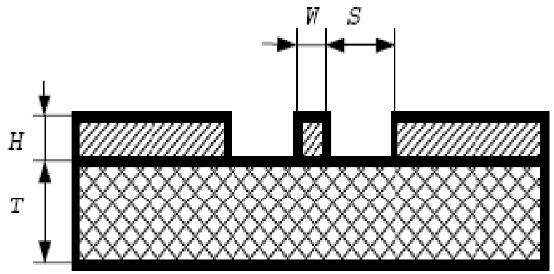
[1]S. Bhattacharjee et al., IEE Trans. on Plasma Science, Vol.32, No.3, 2004

RF Components Development Using DXRL (2)

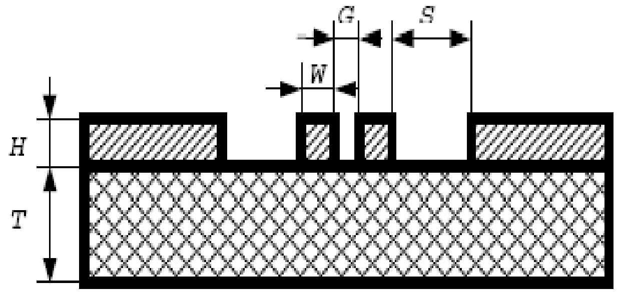
- **High vertical aspect ratio 3-dB coupler[1]**



BKW directional coupler

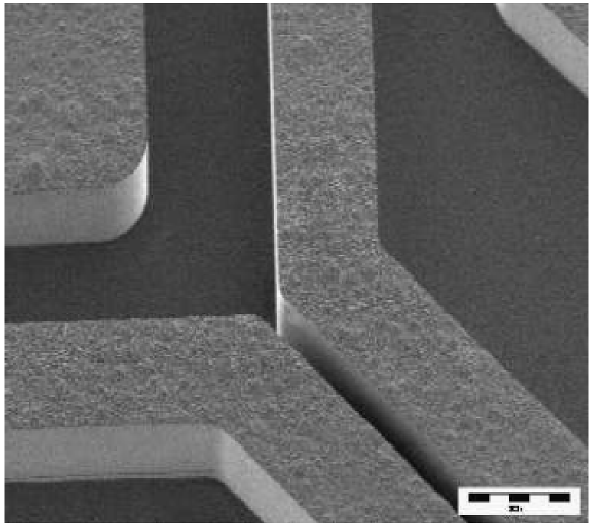


LIGA CPW transmission line



LIGA coupled-line section

Parameter	Transmission Line	3-dB Coupler
W	0.2 mm	0.2 mm
S	0.25 mm	0.56 mm
G	-	0.06 mm
H	0.22 mm	0.22 mm
T	1 mm	1 mm
Length	-	2.26 mm
Z_0	50	50
Z_{0e}	-	121.4
Z_{0o}	-	20.2
ε_{reff}	3.59	-
ε_{reeff}	-	4.27
ε_{roeff}	-	2.7

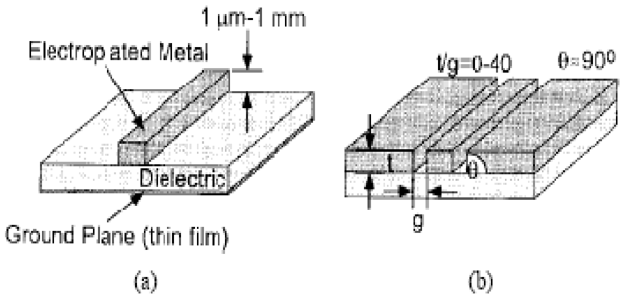


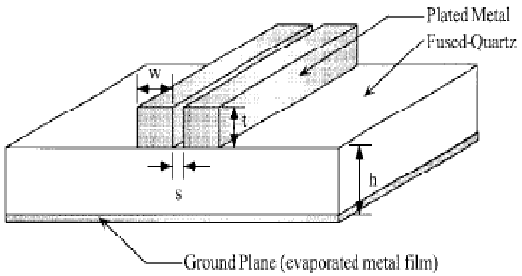
SEM micrograph of the LIGA 3-dB BKW directional coupler

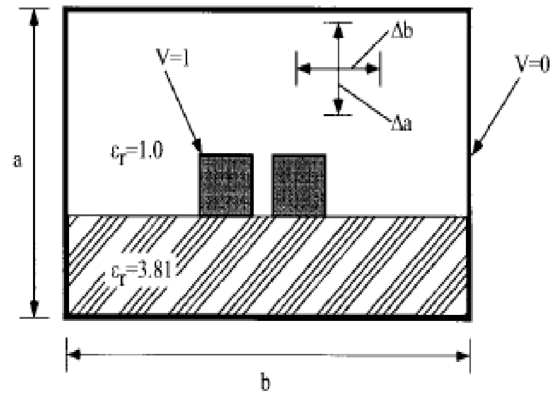
[1] **A. Kachayev at al., ICMENS2003, June 20-23, 2003, Alberta, Canada**

RF Components Development Using DXRL (3)

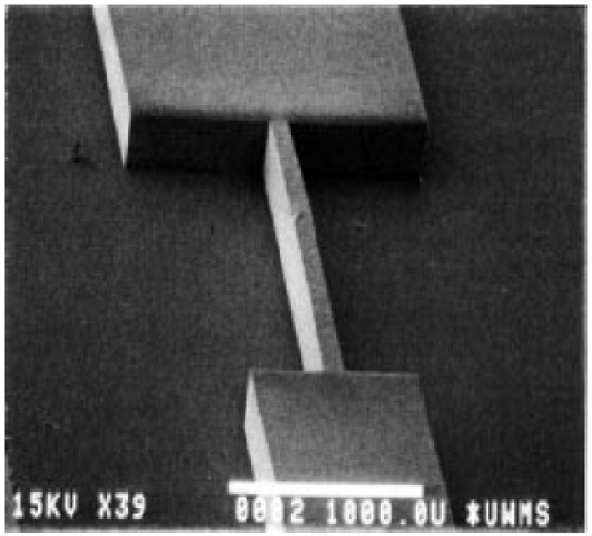
- **Planar transmission lines and filters**[1]

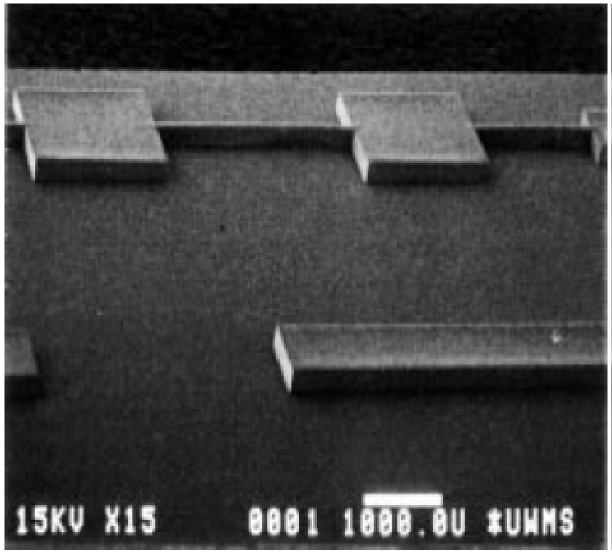


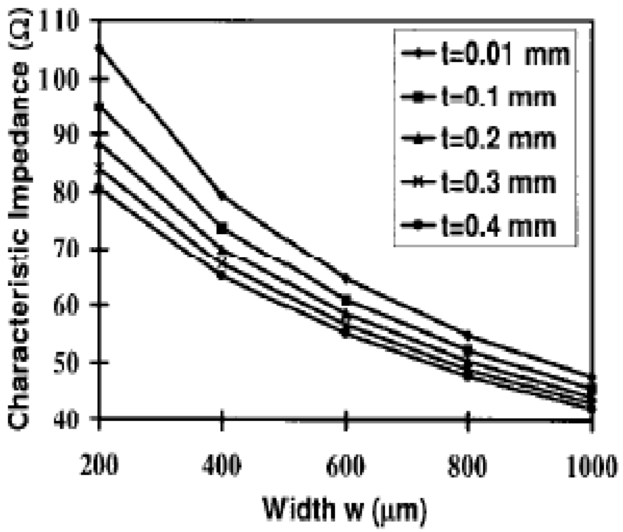




LIGA transmission-line geometry: (a) microstrip line and (b) coplanar waveguide transmission line



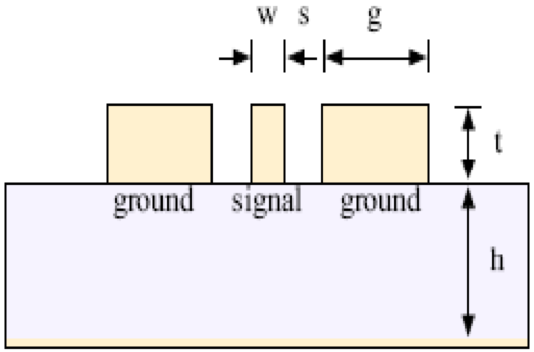


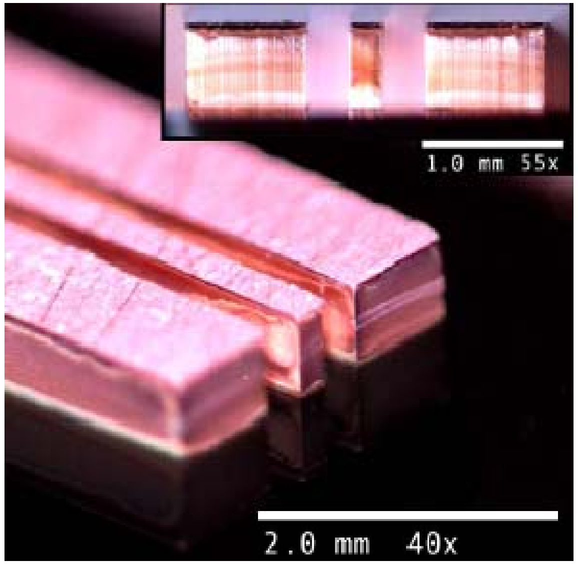


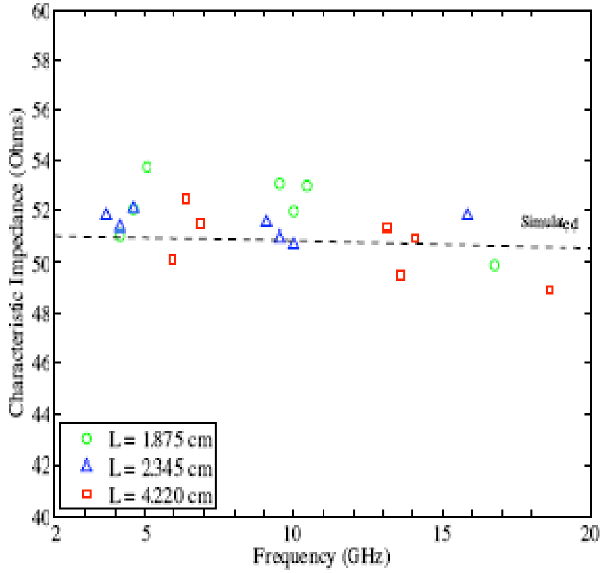
[1] T. Willke at al., IEEE Trans. MTT, Vol.45, No. 10, October 1997.

RF Components Development Using DXRL (4)

- **Low-loss coplanar waveguide and filter**[1]

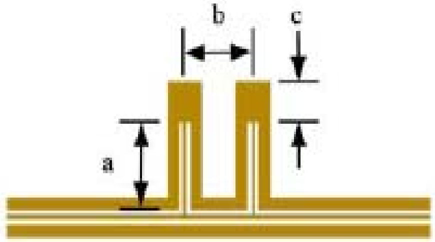




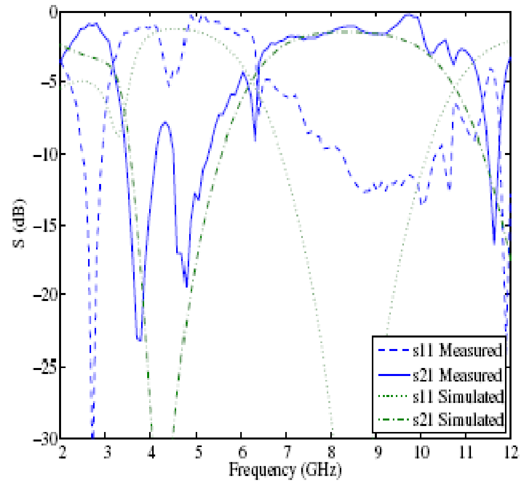


FABRICATED CIRCUIT PARAMETERS

CPW Dimensions		Substrate Values	
w	$238 \pm 5\ \mu m$	ϵ_r	3.75
s	$318 \pm 5\ \mu m$	$\tan\delta$	0.0004
g	$835 \pm 5\ \mu m$	h	1 mm
t	$517 \pm 10\ \mu m$	d	100 mm



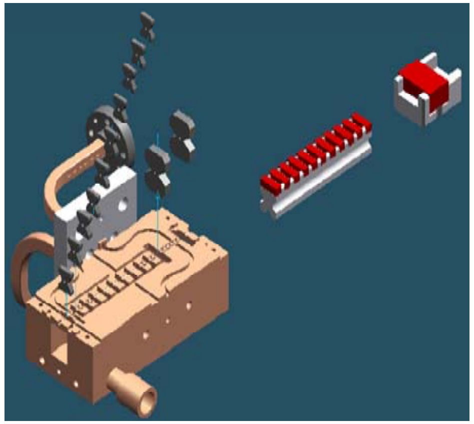
n = 2

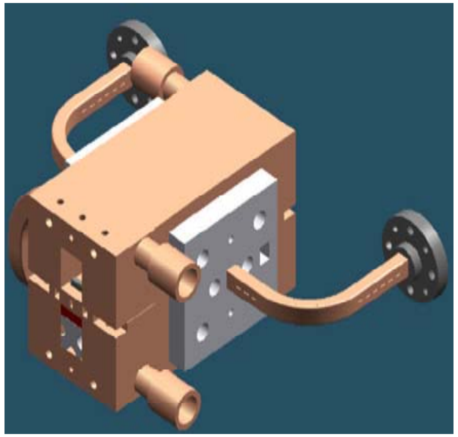


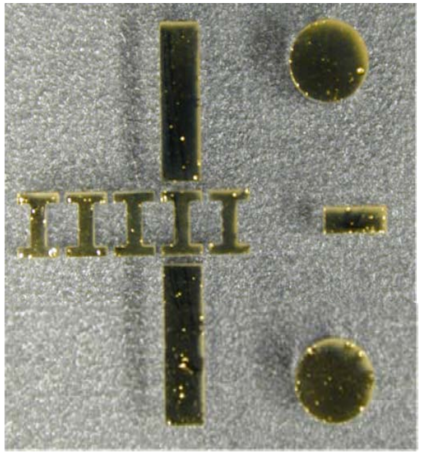
[1] M. Forman, Proc. Of Asia-Pacific Microwave Conf. 2006

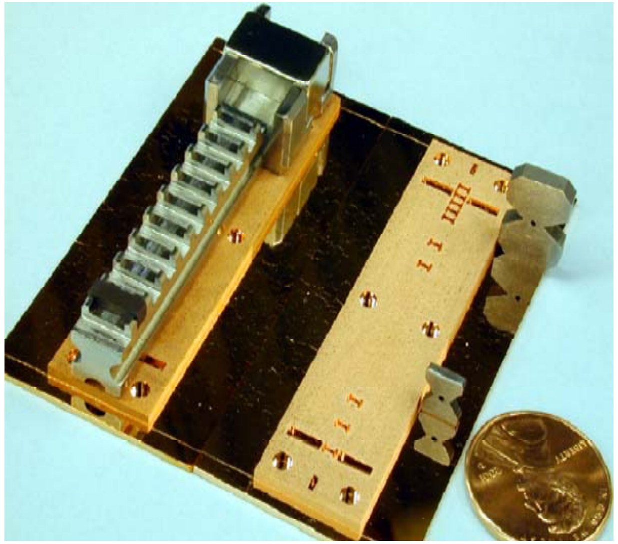
RF Components Development Using DXRL (5)

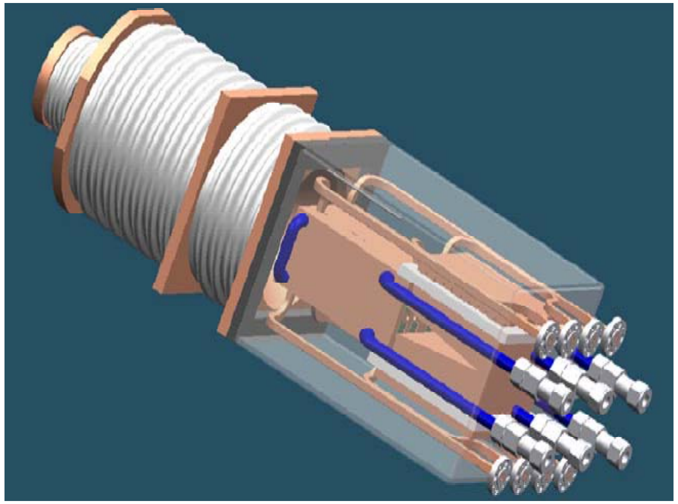
- **W-band klystrino[1]**







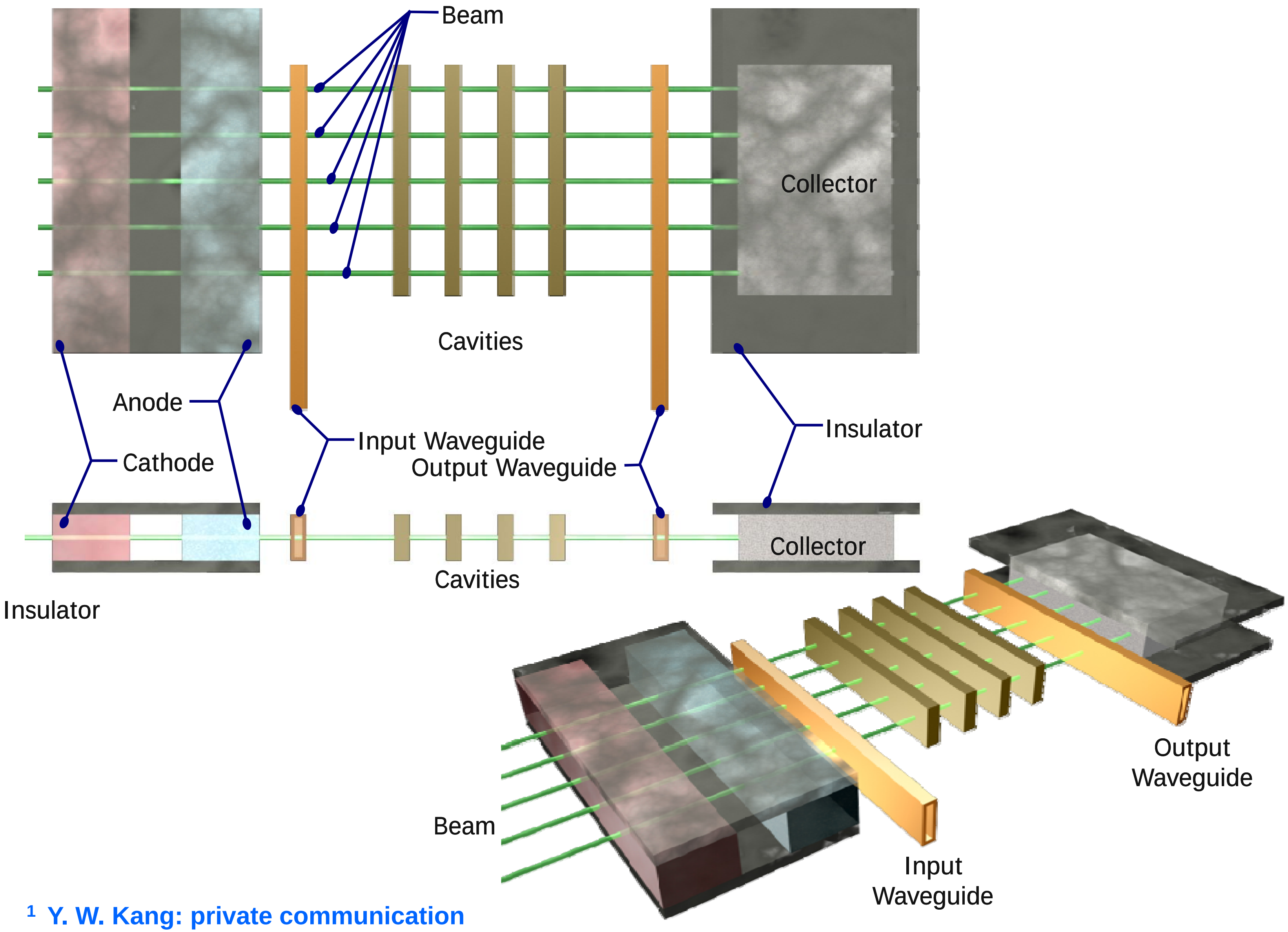




Solid model of klystrino 4-pack (4kW ave.) 4” x 4” x 14”

[1] G. Scheitrum, at al., PPPS 2001, June 2001

Multi-beam Planar Klystron[1]



[1] Y. W. Kang: private communication

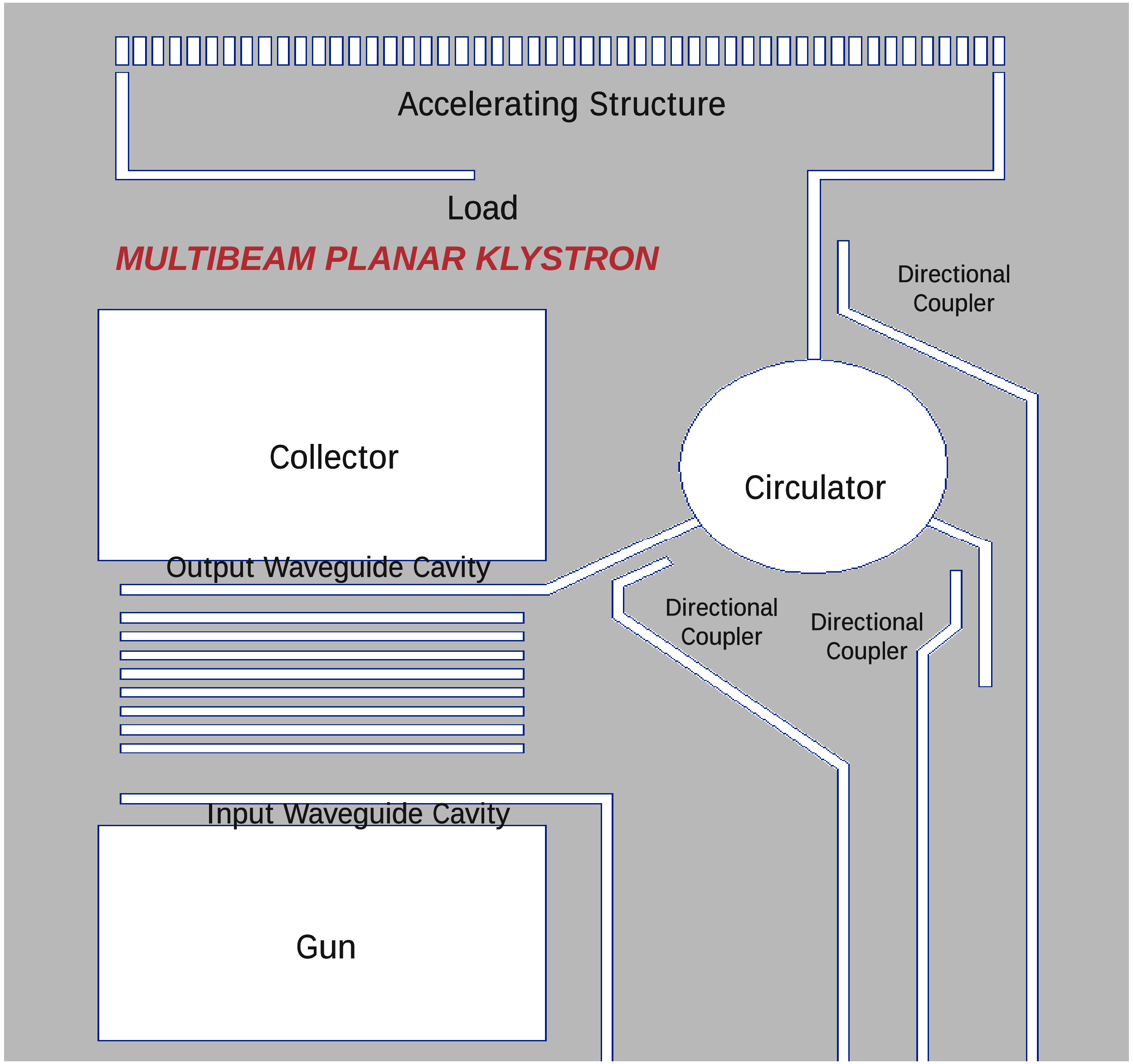
LIGA Possibilities for CLIC

- Could have considerable cost advantage with a single copper substrate that integrates klystron, wave guides, directional couplers, circulators.
- Linac system would be a repetitive mass production fabrication process similar to integrated circuit technology
- Elimination of component technology would reduce installation costs since there would be no klystron, wave guide, or wave guide elements to install in the tunnel.

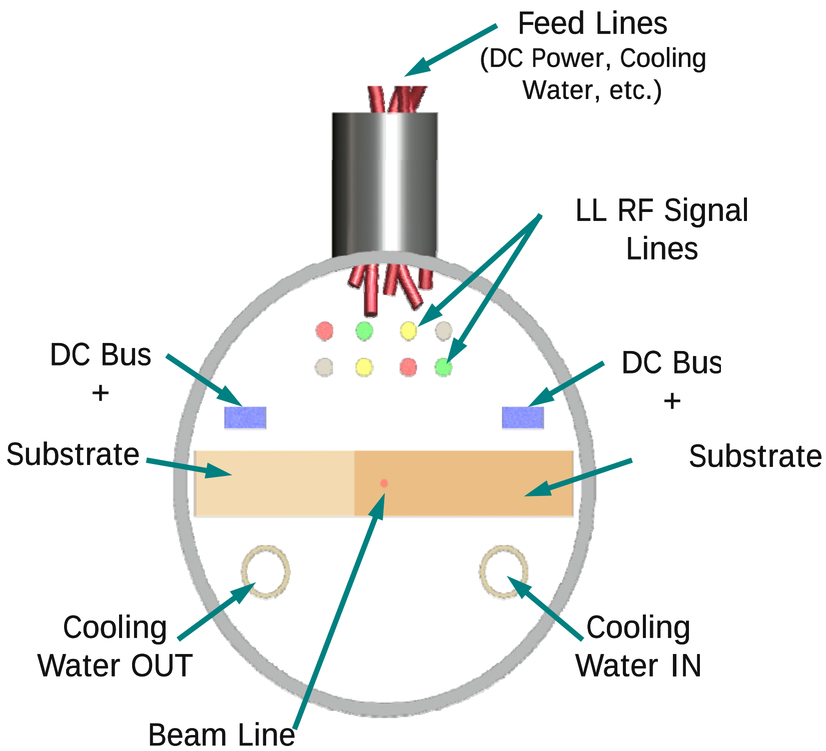
Is LIGA Approach Possible for CLIC?

- Individual components that have been demonstrated using DXRL techniques establish a proof-of-principle, but don't match Linac topology. Redesign and development would be necessary.
- An 18-GHz would require cavity depths that are just beyond the limits of present day DXRL technology if the linac is simply scaled from the original APS work.
- 30-GHz would be within the demonstrated capabilities of LIGA.
- Multi-beam klystron at 18 to 30 GHz has not been studied. There are some references to SLAC sheet beam klystron development in this frequency range, but suitability to a LIGA fabrication process is unknown.

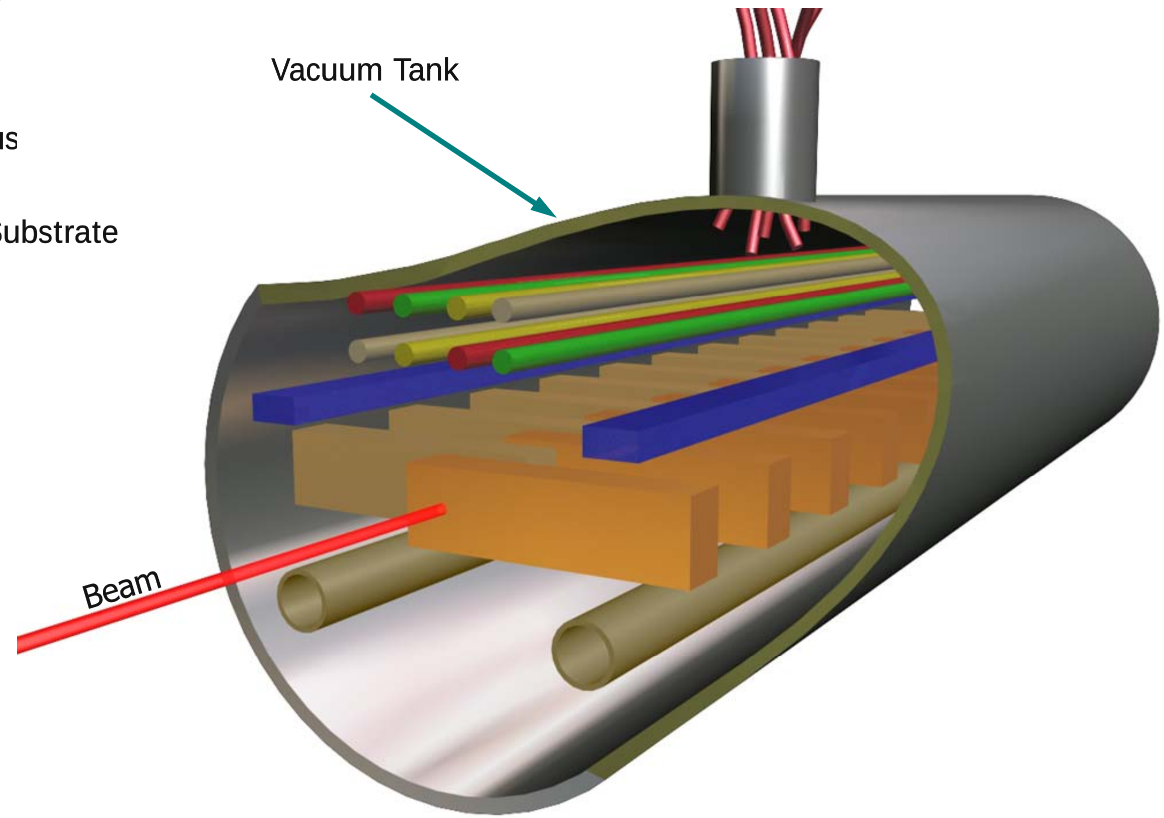
CLIC on a Substrate



CLIC with LIGA?



Cross-Section



Comments on Extrapolation of 120 GHz to CLIC

- **The 1990 LIGA-designed linac had a calculated shunt impedance of 312 MΩ/m and a calculated attenuation factor of 13.5 m^{-1}. This would require a peak power of 2.9 MW in a cavity of 7.4cm for 100 MV/m.**
- **This was close to achievable with a 4-module klystron pack designed by SLAC. The klystron pack was estimated to be about 10 × 10 × 30-cm in size, not including the pulsed modulator.**
- **The physical match between the structure length and the klystron-pack dimensions were a good match at 120 GHz.**

Comments on Extrapolation of 120 GHz to CLIC

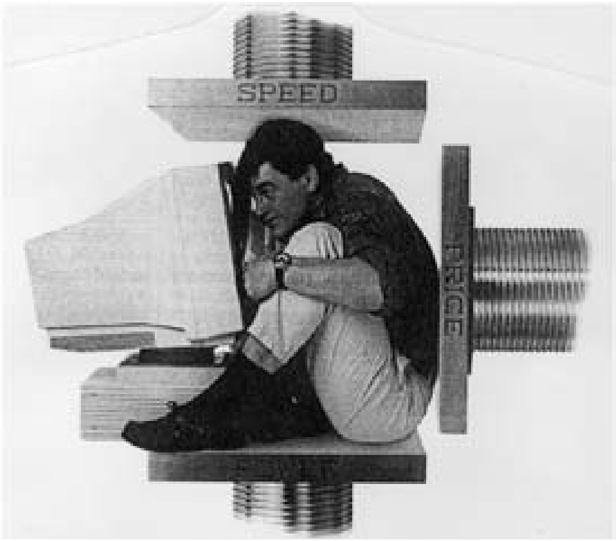
- **At 18 and 30-GHz, however, the shunt impedance goes down with $f^{-1/2}$ and the attenuation length increases with frequency. It is not clear how these can be made to match up.**
- **In general, 100 MV/m is pushing the envelope on power and peak fields. These are unexplored regions for a LIGA structure, although static fields as high as 50 – 100 MV/m have been claimed in the early literature.**

Summary

- **Technology for a fully integrated design in not (yet) available and not likely in the near future.**
- **Hybrid design, ala hybrid integrated-electronic circuits, is closer to being available, requires considerable R&D Even if it was possible, would it make sense since CLIC has already invested great sums on the present design concept?**

Drivers:

- **Price**
- **Performance**
- **Power**



- **Miniaturization**
- **Large-scale production**
- **Cost effective**