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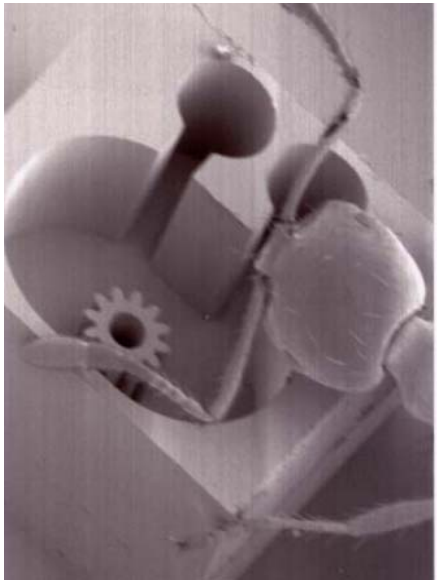
# X-ray-based Microfabrication Techniques for Accelerators



***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*

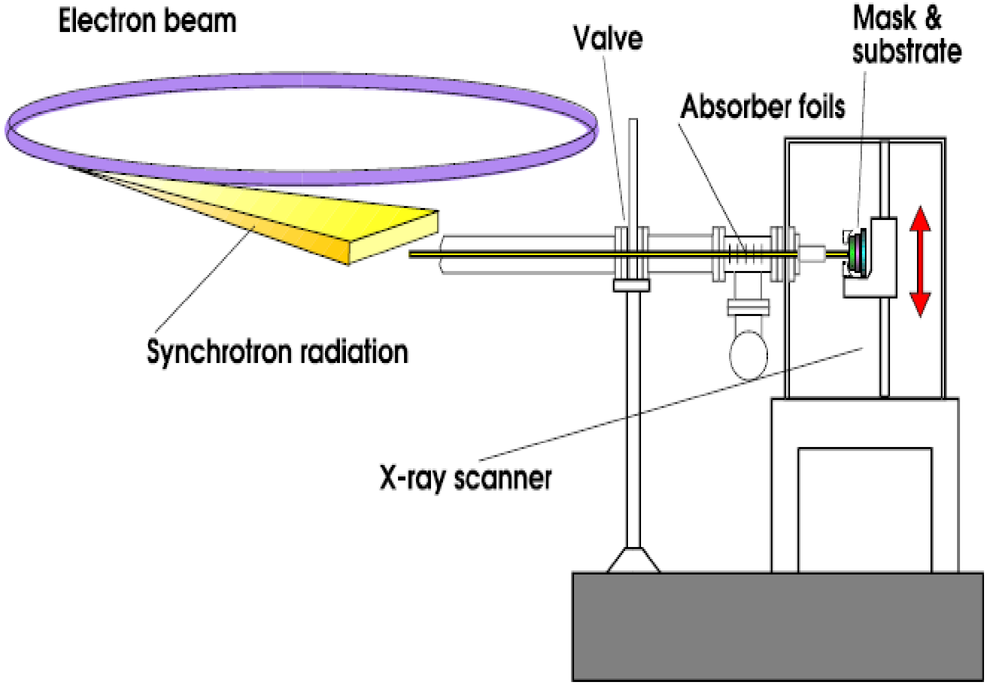
- DXRL,LIGA
- ANL work - history
- Planar structures
- Possible LIGA for CLIC
- Summary

# *What is LIGA?*

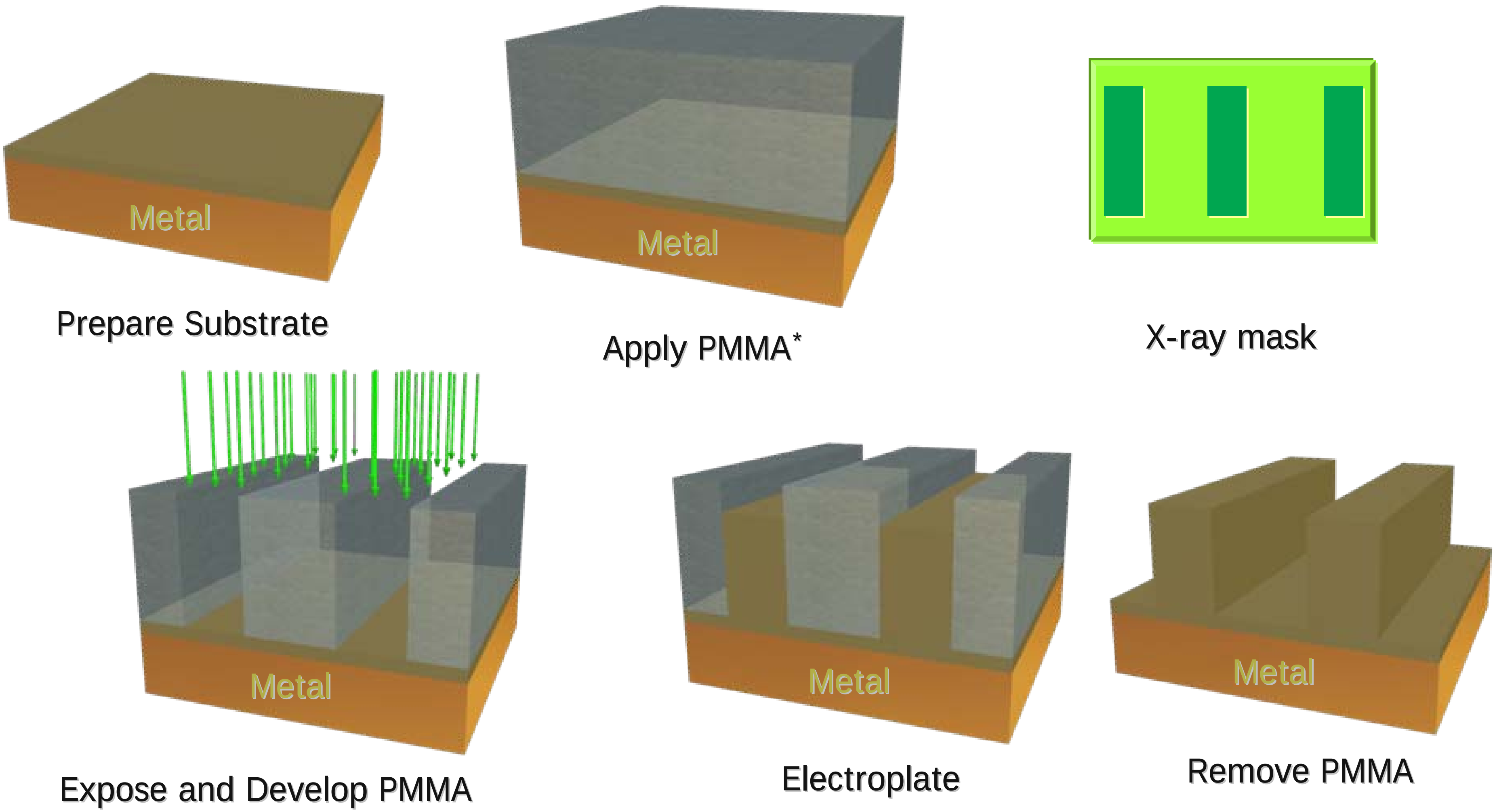
- **LIGA is a process in IC fabrication which involves lithography, electroplating, and molding on a given substrate. (Lithographie, Galvanoformung und Abformug)**
- **LIGA fabricates High Aspect Ratio Structures (HARMS).**
- **The ratio between the height and the lateral size is the aspect ratio (e.g.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




*poly-methylmethacrylate

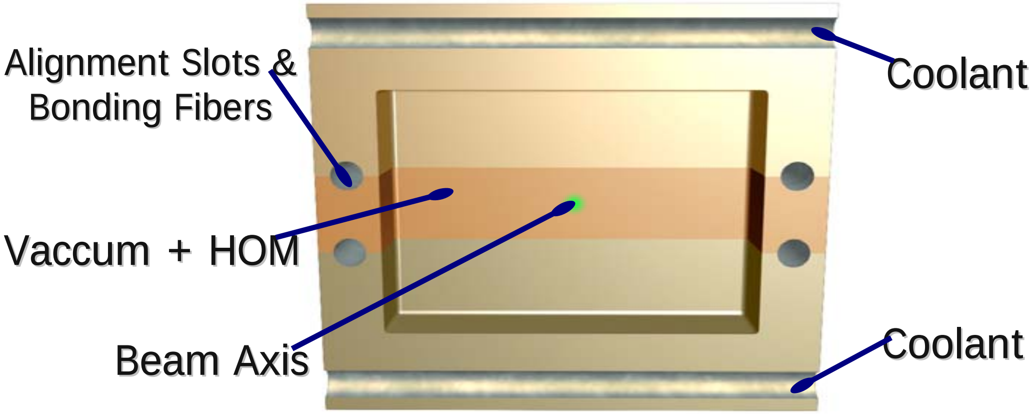
# *ANL Work - History*

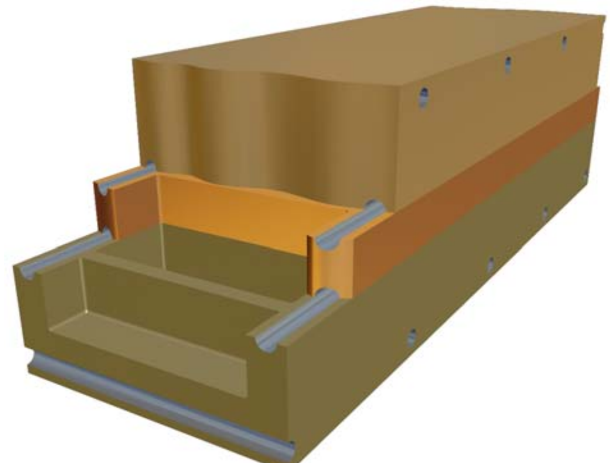
- **120-240 GHz Linac development using deep x-ray lithography (DXRL) techniques (LIGA) in 1991**
- **Developed TW planar –linac parameters in collaboration with Heino Henke of TUB in 1992**
- **Successfully built several 2π/3 structures in frequency range of 108-240 GHz using DXL techniques.**
  - **Demonstrated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

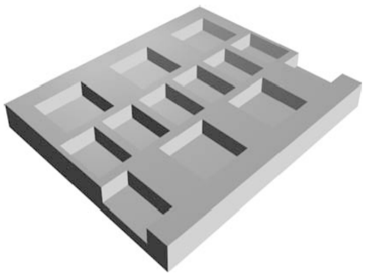
# ANL Work – History (2)

- 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.

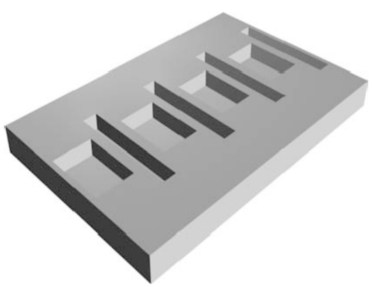
# 3-D Conceptual Planar Structure



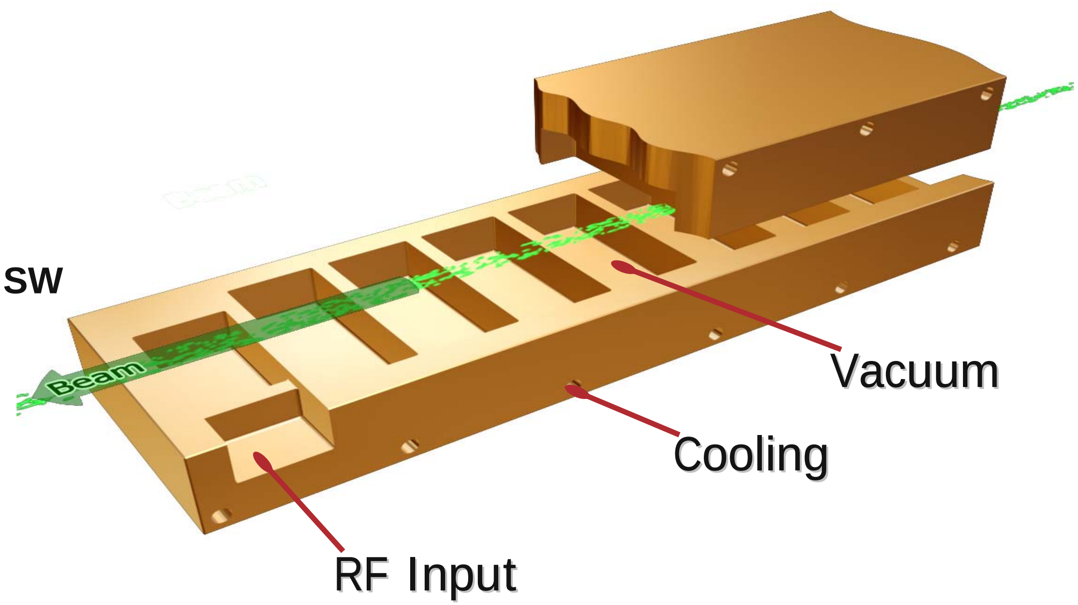





**Lower half of a Side-coupled planar SW Structure**

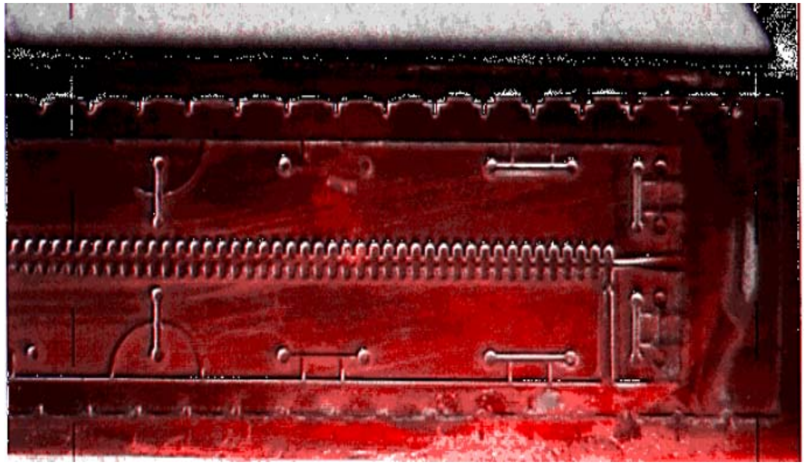


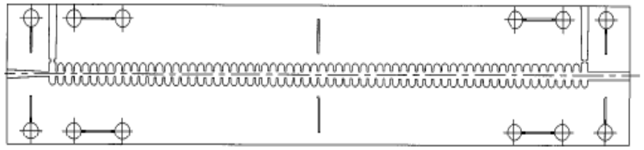
**Lower half of an on-axis planar SW structure**

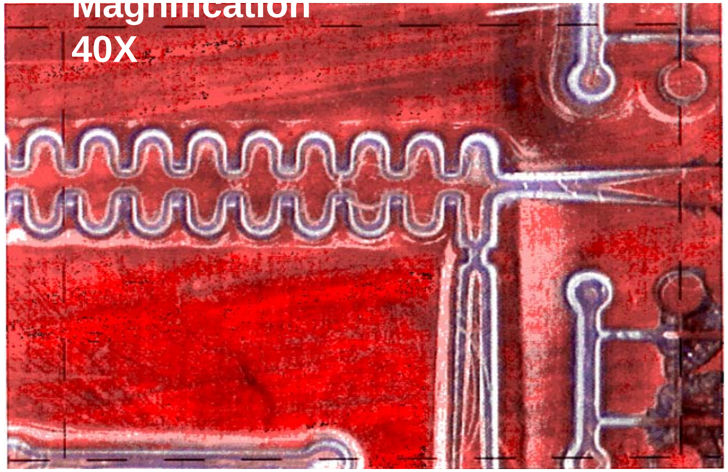


# PMMA Masks with DXRL: 94 GHz CG [1]

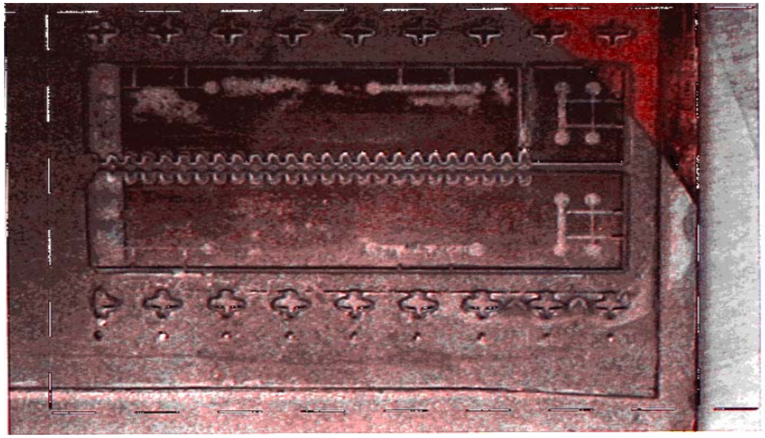
- **Long structure (66 cells)**

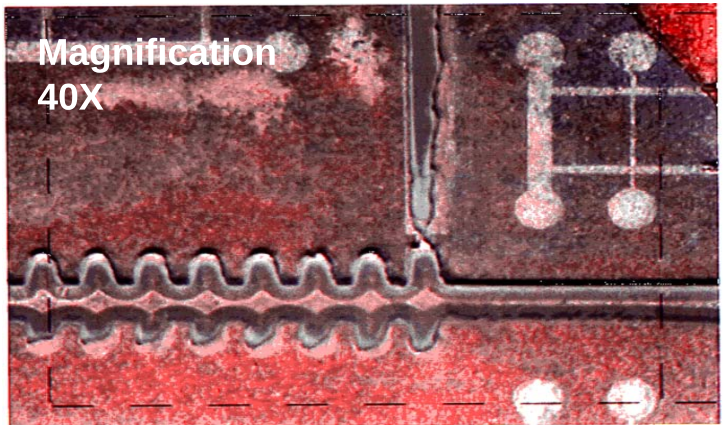







- **Short structure (30 cells)**

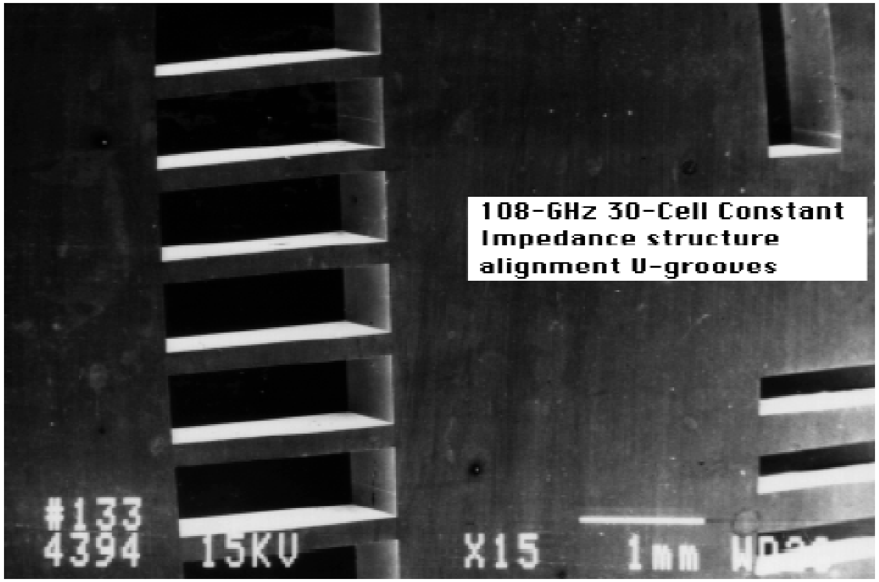




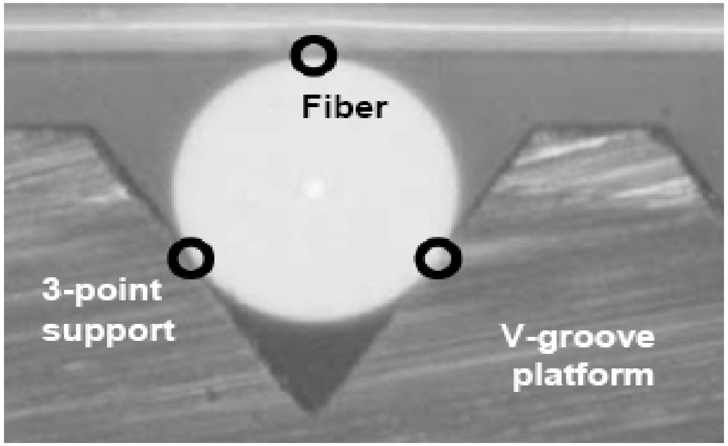

[1] J. Song, at al., Proc. Particle Accel Conf., Vancouver, B.C., Canada, 1997

# CI cavity[1]

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




SEM image of 108-GHz CI structure

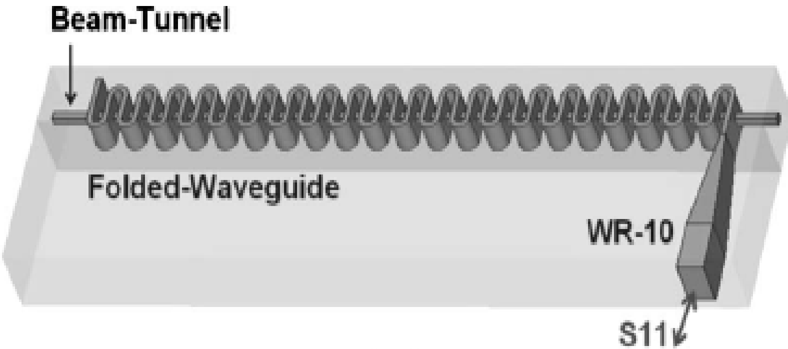



| | | |
|---|---|---|
| Frequency | $f$ | 108 GHz |
| Shunt impedance | $R$ | 312 MΩ/m |
| Quality factor | $Q$ | 2160 |
| Operating mode | TW | $2\pi/3$ |
| Group velocity | $v_g$ | 0.043 C |
| Attenuation factor | $\alpha$ | 13.5 $m^{-1}$ |
| Accelerating gradient | $E$ | 100 MV/m |
| Peak power |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

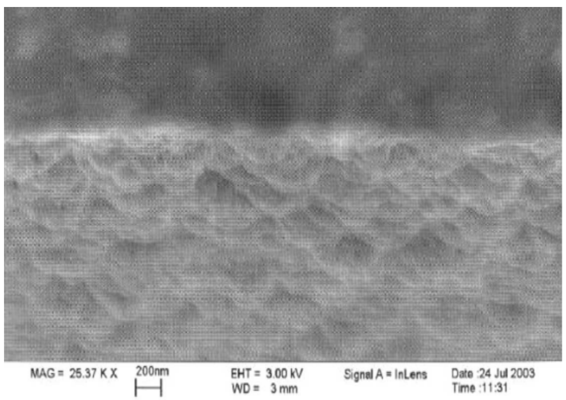
[1] A. Nassiri, at al., Proc. Int. Electron Devices Meeting, Washington, DC, December 1993

# RF Components Development Using DXRL

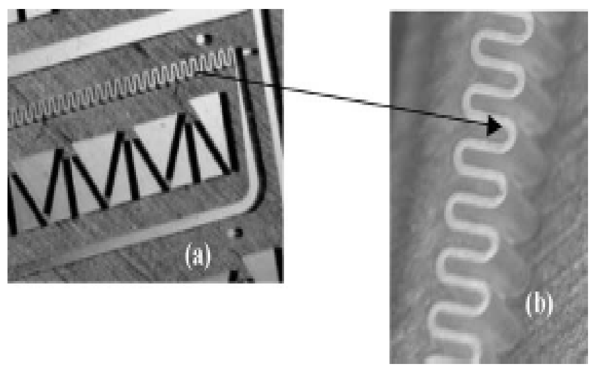
- **Folded Wave Guide TWT Sources for THz Radiation[1]**

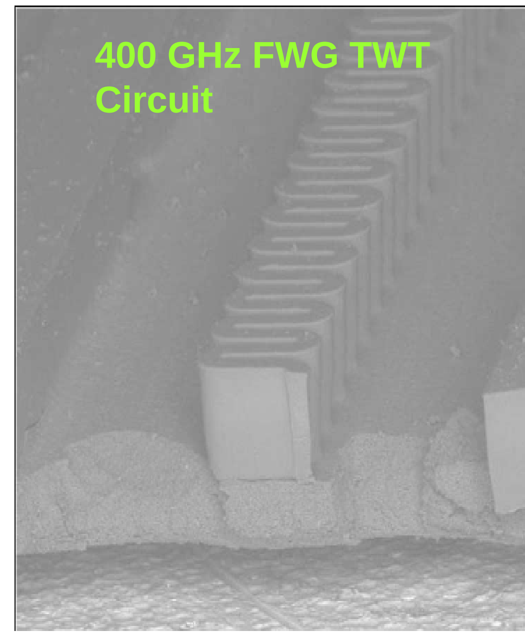



| Quantity | Value |
|---|---|
| $L_{tot}$ (cm) | 1.01 |
| $L_{wg}$ (cm) | 0.055 |
| Number of folded waveguide cavities | 154 |
| Approximate time to complete one complete path, $t_p$ (ns) | 0.19 |
| Total simulation time $t_{tot}$ (ns) | 1.71 |
| Average number of path periods, $n_{tp}$ | 9 |




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



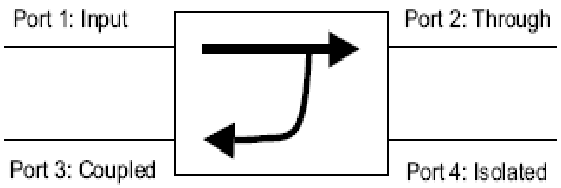




**HAR mold for cu electroplating with a 250-μm high wall and a 100-μm circuit pitch**

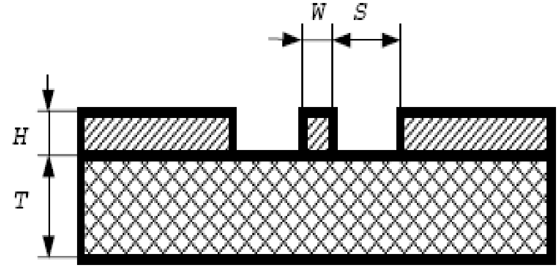
[1]S. Bhattacharjee et al., IEE Trans. on Plasma Science, Vol.32, No.3, 2004

# RF Components Development Using DXRL ( 2)

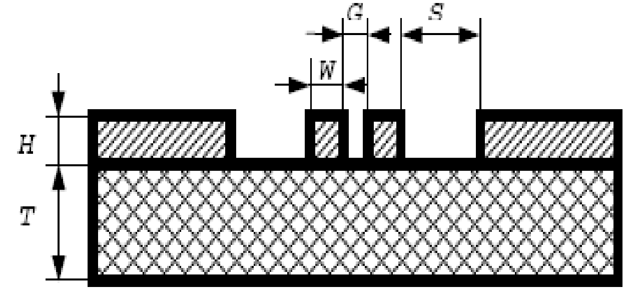
- **High vertical aspect ratio 3-dB coupler[1]**




**BKW directional coupler**

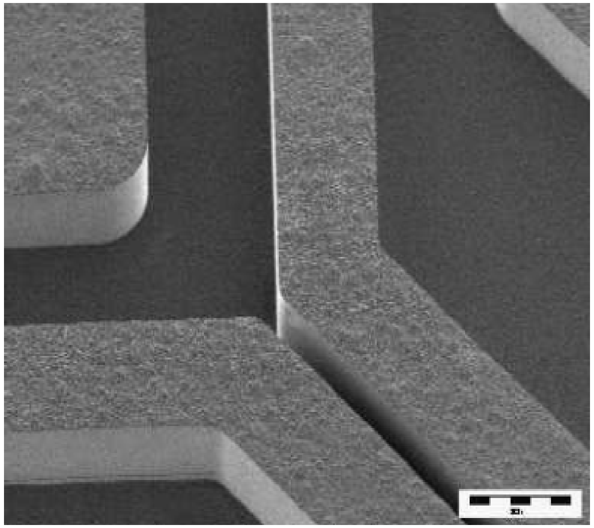



**LIGA CPW transmission line**




**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 |
| $\varepsilon_{r,eff}$ | 3.59 | - |
| $\varepsilon_{re,eff}$ | - | 4.27 |
| $\varepsilon_{ro,eff}$ | - | 2.7 |

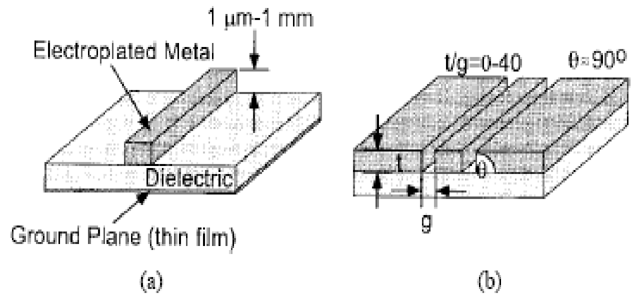


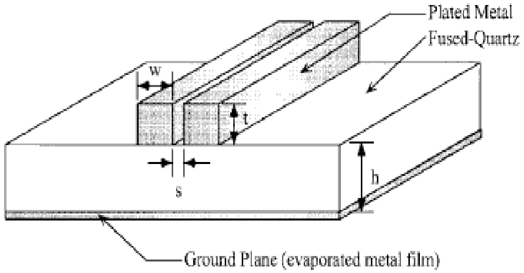
**SEM micrograph of the LIGA 3-dB BKW directional coupler**

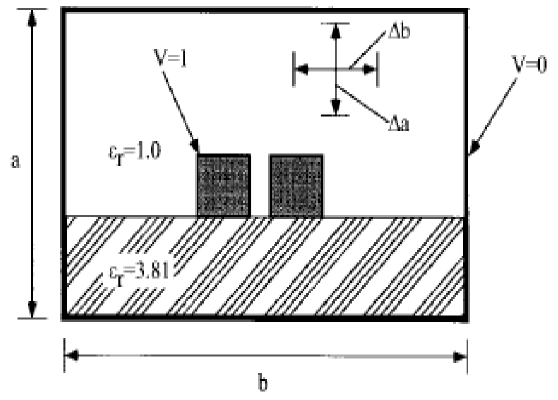
[1] A. Kachayev at al., ICMENS2003, June 20-23, 2003, Alberta, Canada

# RF Components Development Using DXRL ( 3)

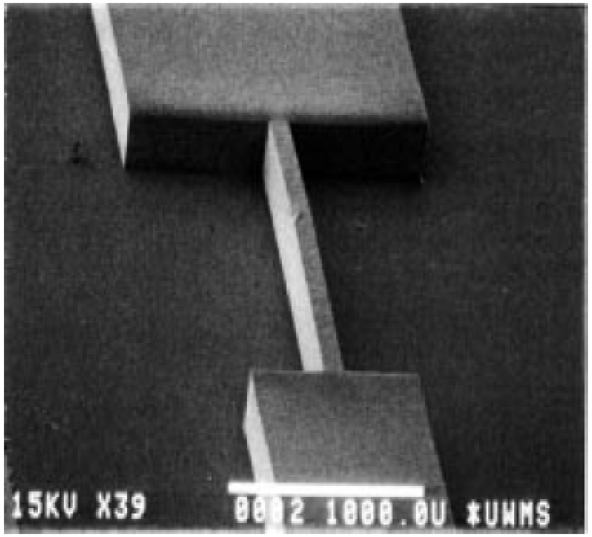
- **Planar transmission lines and filters[1]**

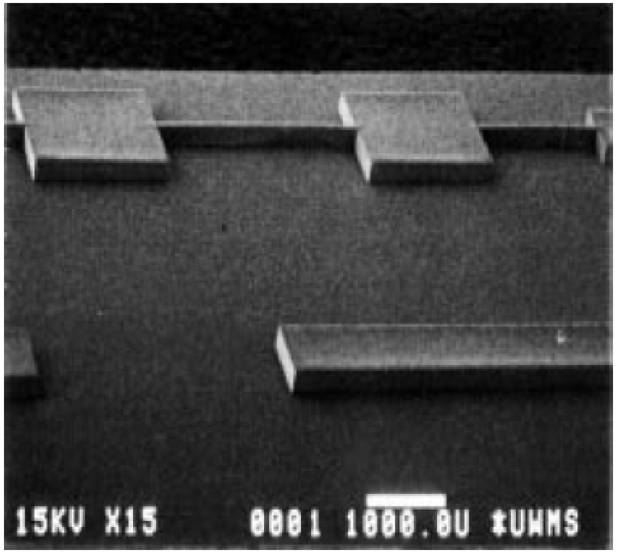


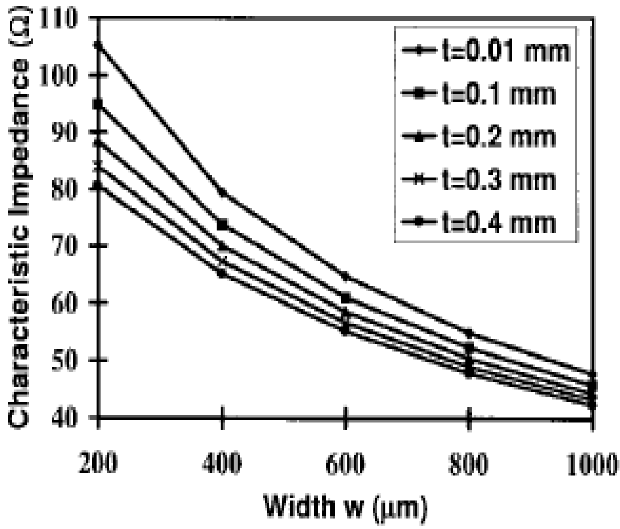




**LIGA transmission-line geometry: (a) microstrip line and (b) coplanar waveguide transmission line**



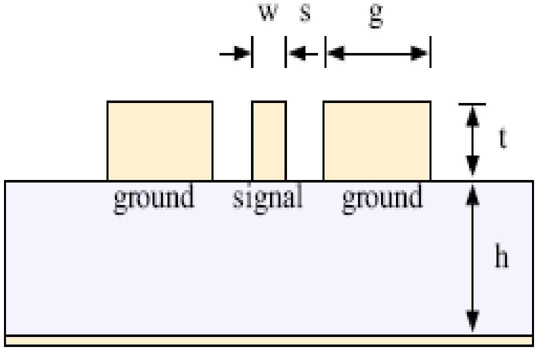



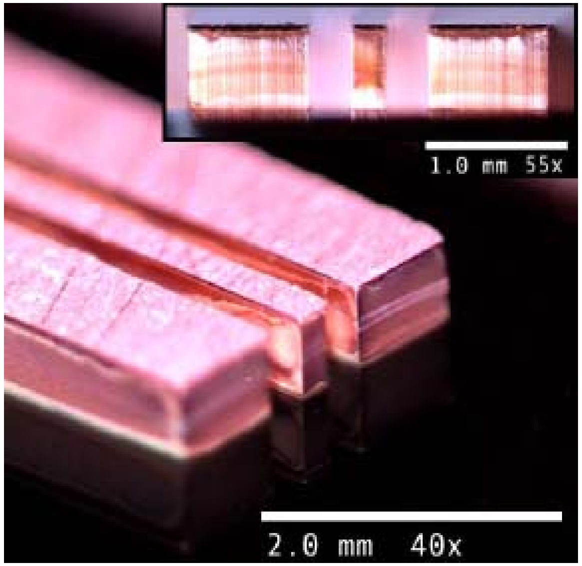



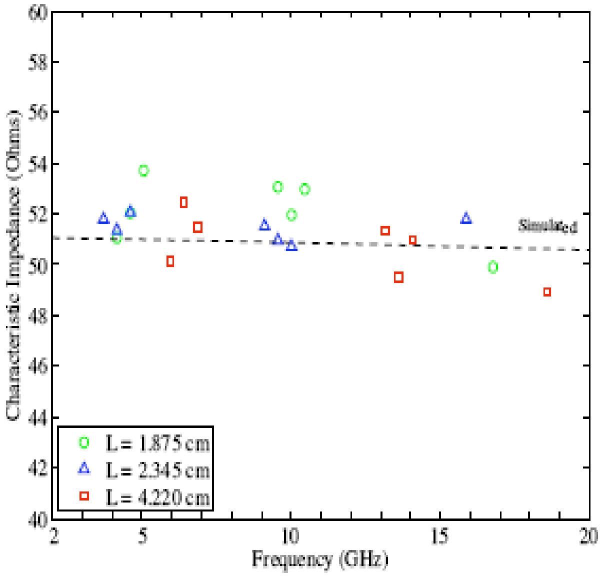

[1] T. Willke at al., IEEE Trans. MTT, Vol.45, No. 10, October 1997.

# RF Components Development Using DXRL ( 4)

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

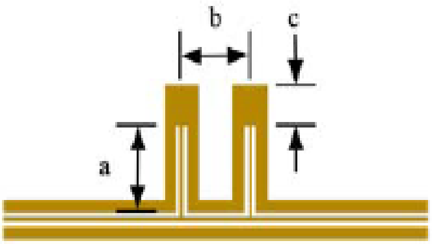


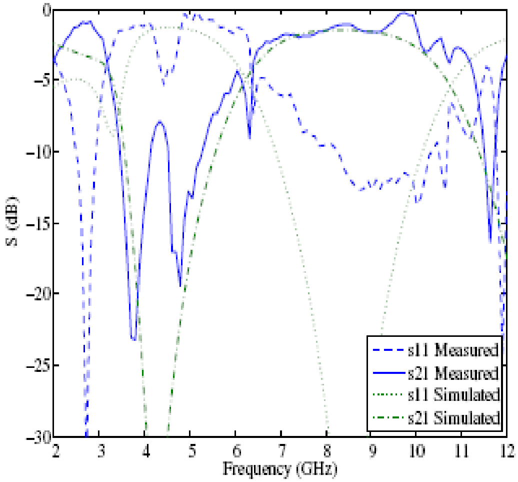




FABRICATED CIRCUIT PARAMETERS

| CPW Dimensions | | Substrate Values | |
|---|---|---|---|
| $w$ | $238 \pm 5$ µm | $\epsilon_r$ | 3.75 |
| $s$ | $318 \pm 5$ µm | $\tan \delta$ | 0.0004 |
| $g$ | $835 \pm 5$ µm | $h$ | 1 mm |
| $t$ | $517 \pm 10$ µm | $d$ | 100 mm |



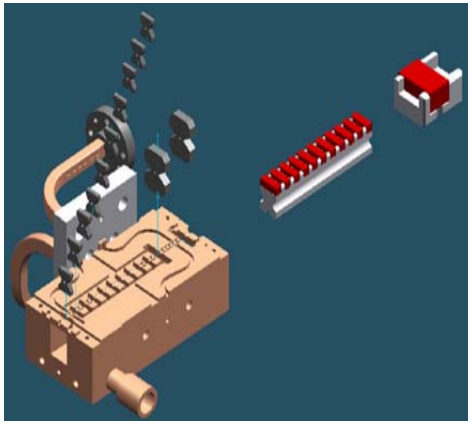
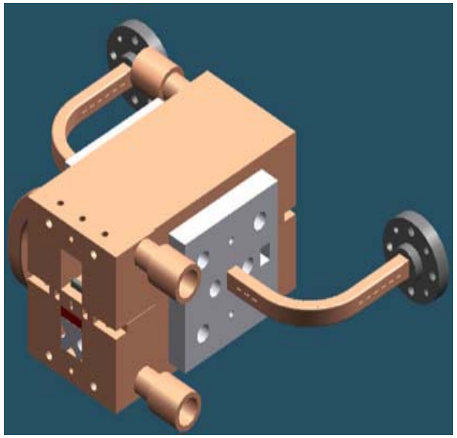
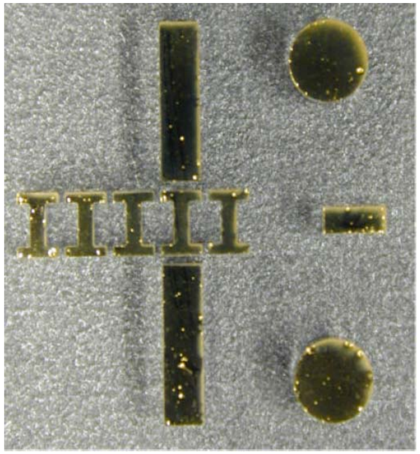
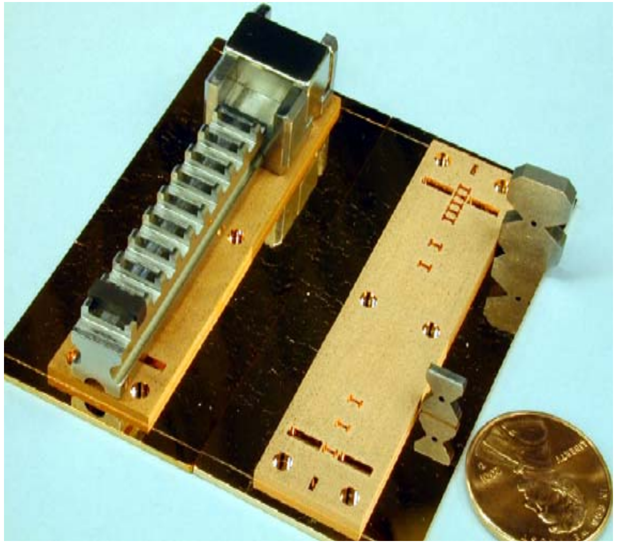
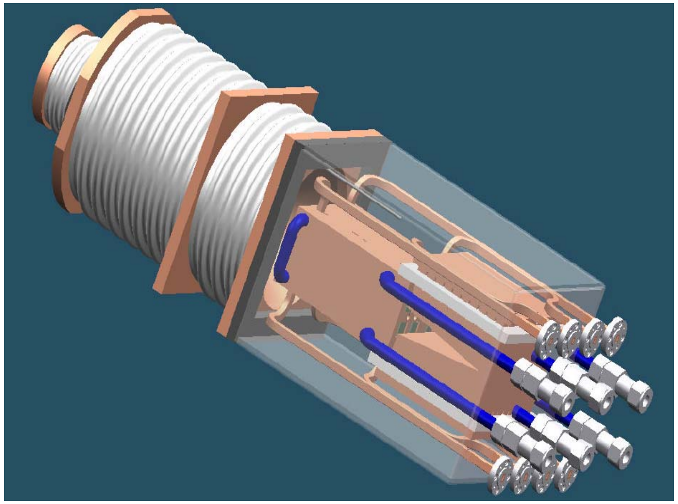

n = 2




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

# RF Components Development Using DXRL ( 5)

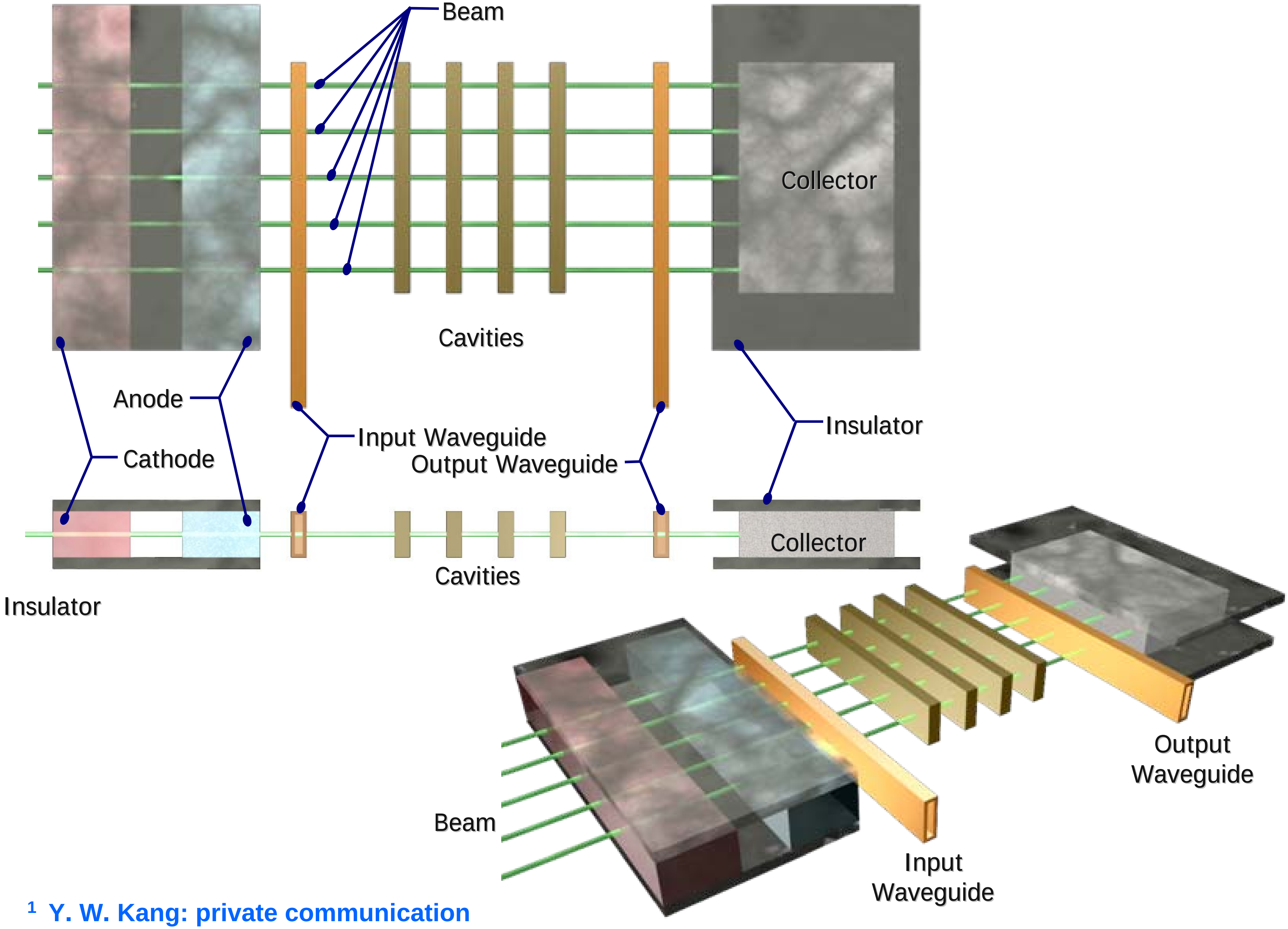
- **W-band klystrino**[1]

**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

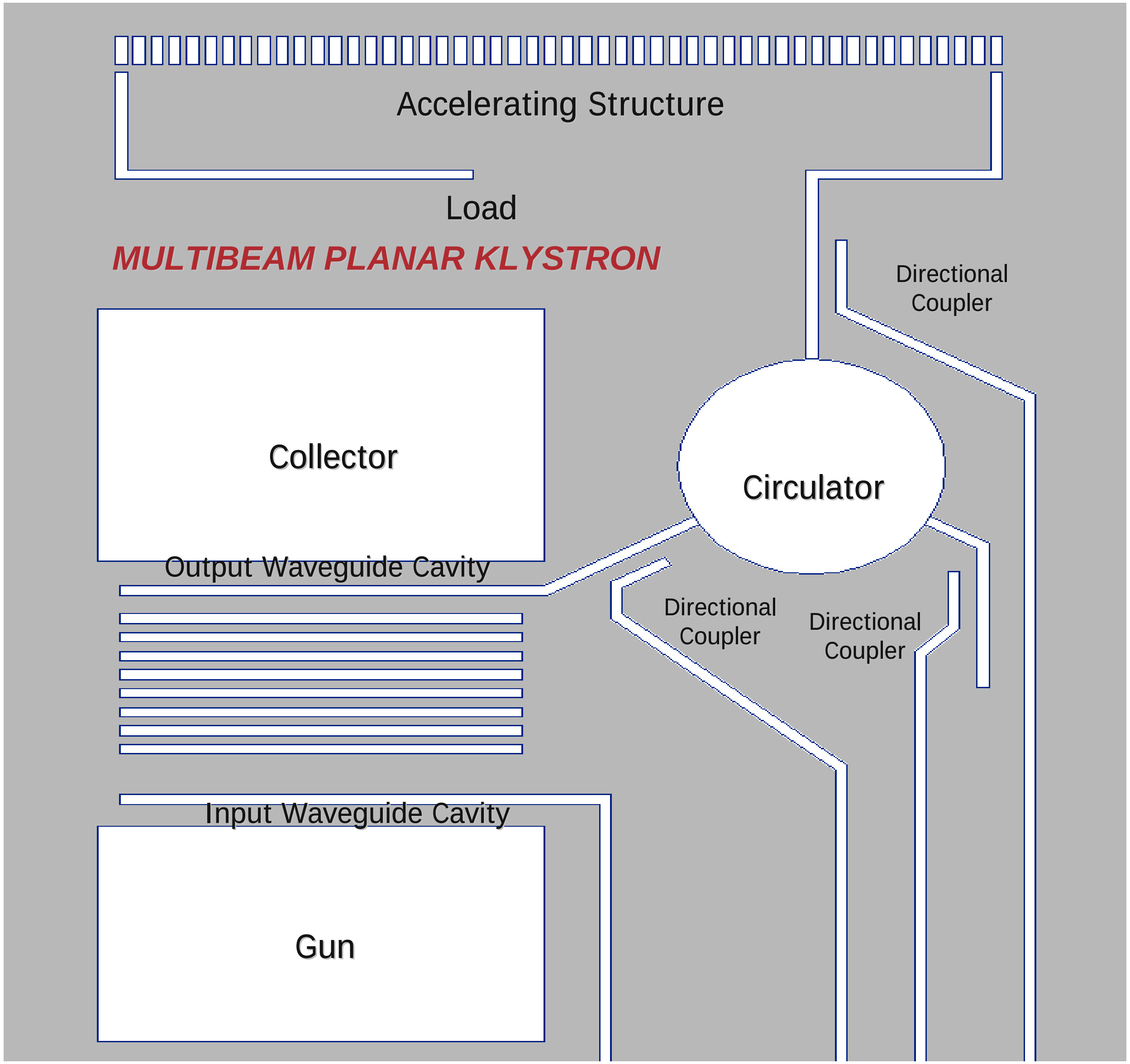
# *LIGA Possibilities for CLIC*

- **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.**

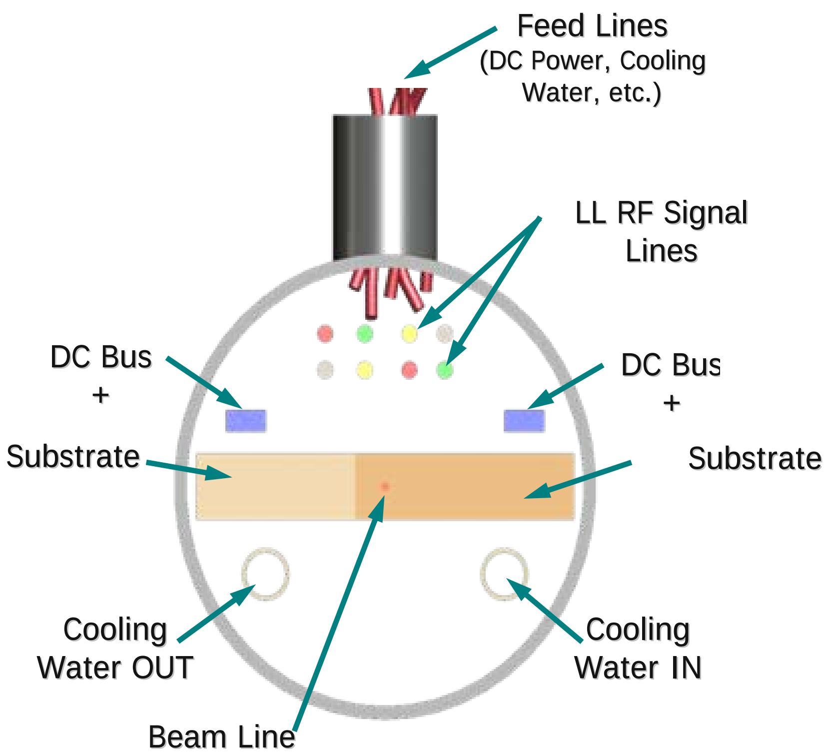
# *Is LIGA Approach Possible for CLIC?*

- 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.

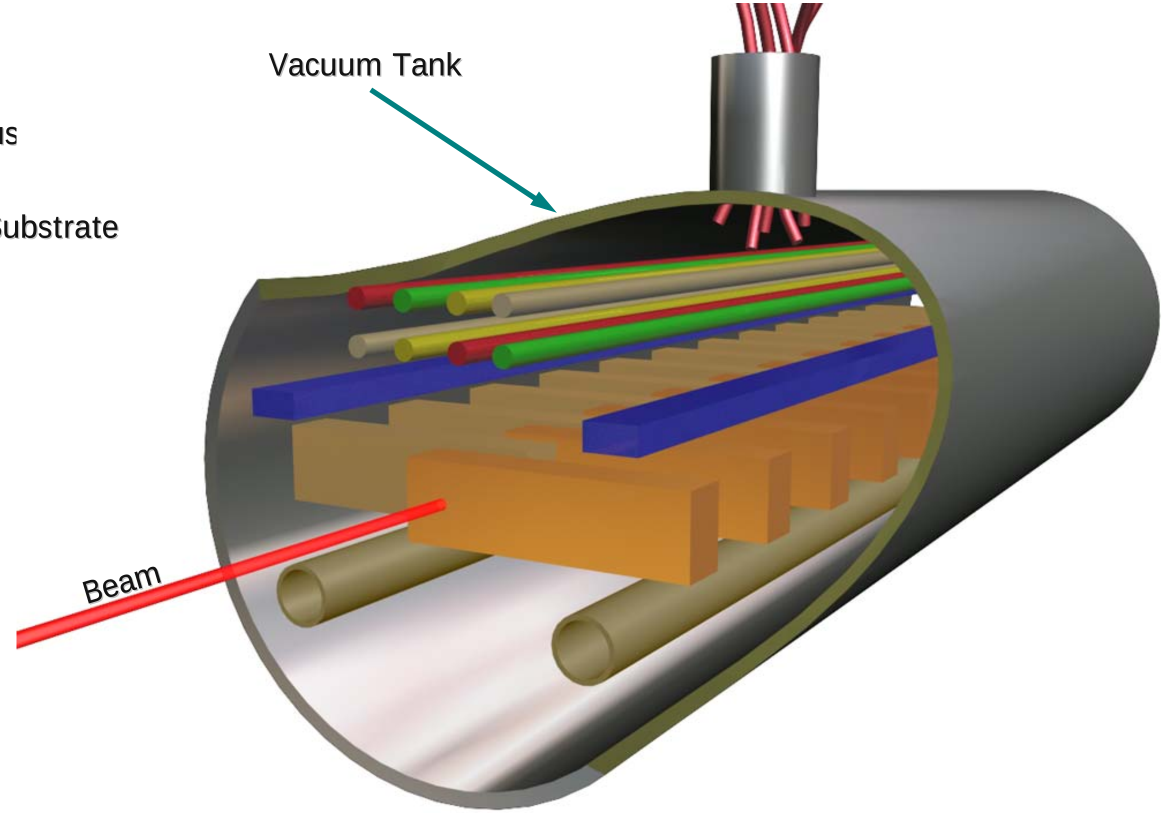
# CLIC on a Substrate



# 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*

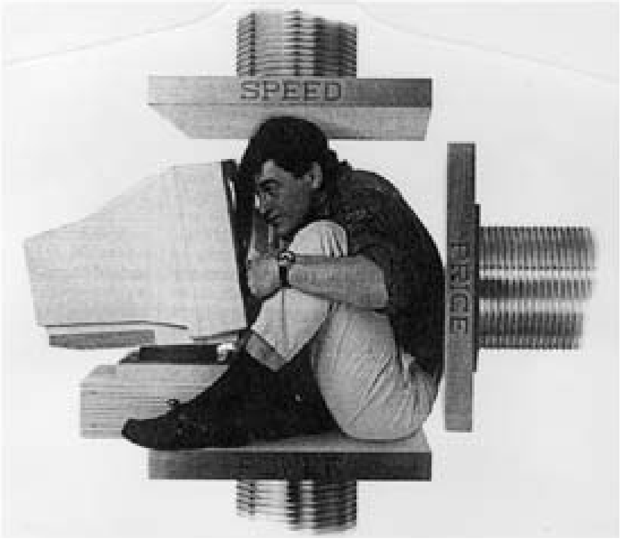
- **At 18 and 30-GHz, however, the shunt impedance goes down with $f^{-1/2}$ and the attenuation length increases with frequency. It is not clear how these can be made to match up.**
- **In general, 100 MV/m is pushing the envelope on power and peak fields. These are unexplored regions for a LIGA structure,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