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ABSTRACT

Conventional millimeter amplifiers (coupled-cavity TWTs or gyro-klystrons) are limited in power by the maximum current that can be accommodated in a single beam. Cathode current density, beam optics, and the magnetic field necessary to confine the beam, combine to limit beam current and add cost and bulk to the device.

If the microwave source is designed as a pulsed klystron operating at a high voltage, larger lateral as well as axial dimensions can be employed. Beam optics become easier and permanent magnet periodic (PPM) focusing is possible. A higher efficiency also results, because of the low perveance. A number of klystrons can then be fabricated on single substrate, using a deep-etch lithography technique. They can be water-cooled individually, and operated in parallel. Several such modules can be stacked to form a klystron "brick," requiring a relatively low voltage for the peak and average power produced. The "brick" can be provided with a single output, or with individual, spatially-combined radiators.

The design of a 4 x 10 x 1.5-inch module producing 500 kW peak, 500 W average at 91 GHz, and operating at 120kV, 10 A, will be described.

Keywords: klystrons, millimeter wave, quasi-optical combining, sintering, W-band, deep etch lithography, LIGA

1. BACKGROUND

Microwave amplifiers capable of substantial power at a 3-mm wavelength are scarce and very expensive. Currently, one has a choice between coupled-cavity TWTs, producing 5 kW peak and 500 W average, and one of several types of gyroklystrons. The latter have outputs ranging from 2 kW CW to 60 kW peak. These sources employ a single, powerful electron beam, which must be confined to a very small cross-section or spun to very high rotational energy. Either way, high magnetic fields are required, as well as very precise electron optics. Power densities are extremely high and advanced cooling designs are required. This contributes to weight and high cost.

Bandwidths of either slow or fast wave devices do not exceed 0.5 percent and overall efficiencies are of the order of 25%. This figure does not include the electromagnet power in the case of the CCTWT, while the helium-cooled superconducting magnet for the gyroklystron poses some problems, if the tube is to be part of a fielded system.

There are a number of military, commercial and scientific applications for W-band sources. If the cost of prototypes were lower, and the devices could be extensively evaluated, or if there were a promise of substantially reduced costs in production quantities, then the expectation would be that millimeter-wave power would be available soon, at reasonable cost. Some very interesting radars, ceramic sintering processes, or accelerators could then be realized. As it is, very few prototypes have been made; and no significant investment in engineering for manufacture is being considered by industry or government.

2. LIGA FABRICATION

A recent development in deep-etch lithography offers an alternative: Using high energy X-rays (synchrotron radiation), together with an electroforming process, it is possible to fabricate planar rf structures, usable as interaction circuits of klystrons or coupled-cavity TWTs. Developed in Germany, this technique is called LIGA (for Lithographie, Galvanoformung, Abformung)[1]. The process is related to the fabrication of semiconductor integrated circuits and requires similar tooling, in addition to a high-energy light source and electroplating equipment. Cavities and slow-wave structures with dimensions of the order of a millimeter can be formed with tolerances of a few microns and finishes of 100-2000 angstroms. Although synchrotron sources are sometimes

[1] "Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming, and plastic moulding (LIGA process)" E.W. Becker, W. Ehrfeld, A. Maner and D. Muenchmeyer. Kernforschungzentrum Karlsruhe. Microelectronic Engineering 4 (1986) Elsevier Science Publishers B.V. (North-Holland)

available at no cost, obviously, the technique has high tooling costs, but after an initial investment, it allows large production quantities to be made, reproducibly and at a relatively low incremental cost. The process is shown schematically in Fig. 1. Not shown is another step, which allows the fabrication of secondary molds. These can be used to electroform (galvanoform) many copies of the structures, without the need of additional radiation.

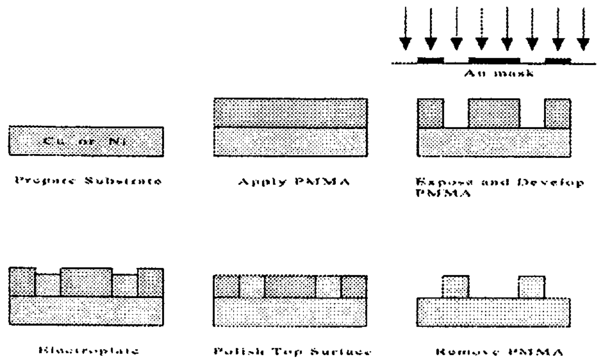


Fig. 1 The LIGA fabrication process.

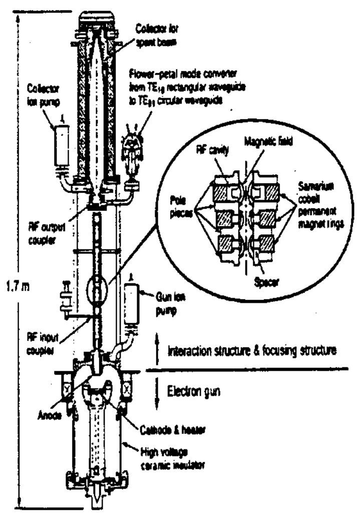
The basic idea in the design of these planar structures is to create the cavity or slow-wave circuit in two halves, the separation being along a plane that does not cross any current paths for the mode employed. The completed structure is constructed by indexing the two halves exactly, leaving a small gap which serves as a pump-out for the drift tube and rf structure. This method allows complex structures to be created through LIGA. At its current stage of development, LIGA allows structure heights of approximately 1 mm (2 mm total internal dimension). These planar structures can be fabricated with only two levels, unlike, for instance, the EDM process, where shapes of arbitrary depth can be achieved. LIGA, however, is capable of 10 times the accuracy and finish of the EDM process.

A LIGA-constructed planar rf structure is the cornerstone of the module scheme for obtaining substantial power at W-band. It is incorporated into a 4x10 inch module consisting of four klystrons, each producing at least 125 kW, at a beam voltage of 120 kV and a beam current of 2.5 A. Modules can be stacked and powered by the same modulator. The outputs are combined for a module total of 0.5 MW.

3. BASIC MODULE DESIGN

Three key design features make the module design and parallel tube operation possible: The first is Periodic Permanent Magnet (PPM) beam focusing. The second is quasi-optical spatial combining of the tube outputs. The third is a "smart tube" feedback and logic system, which controls the drives to the individual klystrons and maintains the correct amplitude and phase relationships for optimum combining.

PPM focusing is commonplace with TWTs, both helix and coupled cavity, but has not been used extensively for klystrons. In general, it is effective with tubes in which the required focusing field and the dimensions of the rf circuit are such that polepiece saturation can be avoided. Recently, a very high power X-band klystron, shown in Fig. 2, demonstrated not only good beam transmission with PPM focusing, but excellent efficiency as well.[2] The key to this success was the low perveance beam, which allowed stable periodic focusing, and a period sufficiently long to accommodate klystron cavities placed between polepieces. The same approach is possible at W-band, with planar instead of cylindrical magnets and polepieces. The polepiece tip controlling the field at the beam can be fabricated extremely accurately, in a separate step of the LIGA process.



50 MW X-Band PPM Klystron Simulation and Test Results

Item	Experiment	Simulation	Unit
Peak RF Power output	56	59	MW
Peak Beam Power	93	91	MW
RF Efficiency	60	65	%
Gun perveance	0.66	0.60	μK
Beam voltage	459	465	kV
Beam current	205	190	A
Intercepted Beam Power @ Rated RF Output	1	0.0	%

Fig. 2 The SLAC 50 MW X-band PPM-focused klystron

Quasi-optical spatial combining at millimetric frequencies has been perfected by a group at the Institute of Applied Physics at Nizhny Novgorod and is a very low-loss combining method at these frequencies. A simple form of it is used to separate the output from the spent beam in very high power millimeter-frequency gyrotrons. In the

[2] G. Caryotakis: "Development of X-band Klystron Technology at SLAC" Invited paper, Particle Accelerator Conference, Vancouver, 1997, SLAC PUB 7548

case of the four-klystron, W-band module, it consists of four horns, which convert the WR10 TE_{10} mode to a quasi-Gaussian beam; four smooth, curved phase-correcting mirrors; two corrugated plane mirrors; another two smooth, curved matching mirrors; and a final corrugated combiner. (see Fig. 3) Total losses for the design are estimated at 5 per cent. The available bandwidth (for the combiner only) can be as high as 5 per cent. Obviously, however, amplitude and phase matching of the individual inputs are extremely important.

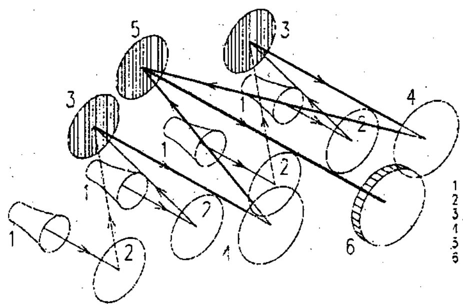


Fig. 3 Four-klystron quasi-optical combiner

To ensure that power combining is accomplished as efficiently as possible, and on a pulse-to-pulse basis, power at various stages of the combining process can be sampled through small holes in the mirrors. The samples can then be fed back to a microprocessor controlling the signals to phase and amplitude correction circuits placed at the input of each klystron. Both the microprocessor and the correction circuits can be placed on small chips and attached to each klystron module. The final klystron "brick," consisting of several modules, in principle, can produce an output of several megawatts of pulsed W-band power. This magnitude of power, at this frequency, justifies the "smart tube" or "neural net" logic that the quasi-optical combiners require.

4. KLYSTRON PARAMETERS

The detailed parameters of individual klystrons are:

Frequency:	91 GHz
Voltage:	120 kV
Current:	2.5 A
Perveance:	0.06×10^{-6}
Output power*	125 kW
Pulse length:	1 μs
Drift tube diameter:	0.8 mm
Beam diameter:	0.5 mm
Cavity gap length:	0.4 mm.
Brillouin field:	2.7 kG
Cathode current density:	15 A/cm^2
Magnetic period:	6 mm
Beam area convergence:	85:1
Plasma wavelength:	40 mm

* The 42.5% total efficiency is a product of a conversion efficiency of 50% and a circuit efficiency of 85%.

The cathode loading and beam convergence parameters are quite conservative and, except for the low perveance and PPM focusing, this is standard klystron design. As indicated above, the high ratio of plasma wavelength to magnetic period should produce exceptionally stable beam confinement. Obviously, the beam voltage is very high for the power produced by a single klystron. It is high because of the low perveance required for PPM-focusing (and for good efficiency). However, it is the PPM focusing feature that makes the module design and tube paralleling possible. With eight or more tubes operated in parallel and producing megawatts, 120 kV can no longer be regarded as a high voltage.

5. SIMULATIONS

A number of simulations and some cold testing have been performed to ensure that the design of the individual klystrons does not contain potential "show stoppers." The results are discussed below:

- **Gain and efficiency**: The one-dimensional, JAPANDISK, large-signal code has been used. The results are shown in Fig. 4. With seven cavities, the klystron is predicted to have a conversion efficiency well over 50% and a gain of about 45 dB.
- **R/Q**: This is a critical parameter, which determines both the gain-bandwidth of the device and the output circuit efficiency. The simulation above assumed R/Q's of 60 ohms for all cavities except the output. A cold test was performed with a simple TM_{01} cavity at X-band, with a gap parallel to its axis, as it would be fabricated by the LIGA process. An R/Q of 76 was measured with no gap, and 69 with a 62-mil spacing (corresponding to about a 10-mil gap in the actual device). For the output cavity, the JAPANDISK simulation assumes a more complex, extended-interaction circuit, consisting of four reentrant cavities, inductively coupled and operating in the 2π mode. The R/Q of a single section of this circuit has been calculated with a MAFIA simulation to be 85 ohms. An R/Q of 270 was used in the simulation, a conservative figure.
- **Gun and PPM optics**: Fig. 5 shows the results of the simulation with DEMEOS. Gun and beam optics are excellent, as one would expect at this low perveance.
- **Polepiece flux density:** An ANSYS simulation predicts that the flux density in the part of the polepiece nearest the beam is only 7.5 kG.
- **Output cavity temperature at full power:** Another ANSYS calculation shows a maximum temperature

rise of 10°C at the full output power of 125 kW and an assumed duty of 0.1 per cent. An output circuit efficiency of about 85% is calculated, based on a Q_0 of 1500 and a Q_{ext} of 270 for the output cavity.

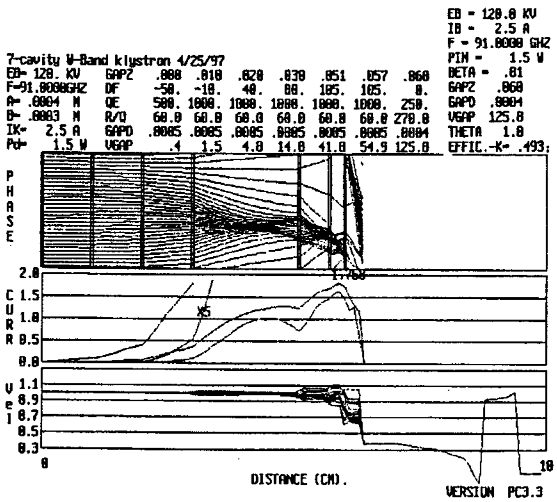


Fig. 4 JPNDisk output showing beam bunching and an efficiency of 49%.

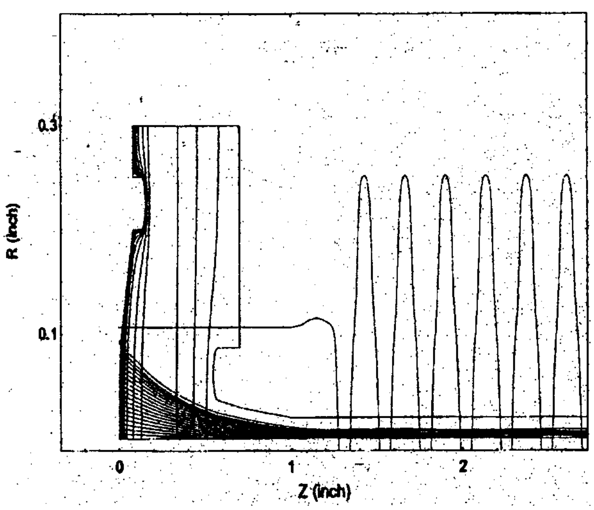


Fig. 5 DEMEOS simulation of electron gun and PPM-focused beam.

6. OTHER DESIGN FEATURES

The mechanical design of the four-klystron module consists of two indexed support plates. These position the klystron halves relative to each other and to the electron guns, serve as the klystron heat sink, and provide the vacuum container for the entire assembly. These indexing features are shown in Fig. 6, for a different type of structure.

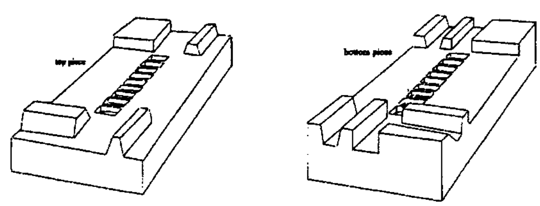


Fig. 6 RF structure halves showing alignment features. (Structure is an accelerator section).[3]

Incorporated into the klystron module plates are vacuum manifolding to allow pumping of the klystron drift tubes, cavities, and waveguides. In addition, micro-channel heat exchanger passages are routed through the plates to cool the klystron collectors and output cavities. The sections of the PPM polepieces adjacent to the cavities and the rf cavities themselves for each klystron are deposited by the LIGA process on two substrates consisting of diffusion-bonded layers of copper and iron-nickel alloy. (Copper is deposited on copper and iron on iron) The two substrates (eight in total for a module) are diffusion bonded or brazed into the support plates. Details of the individual klystron construction are shown in Fig. 7 and a layout of the four-klystron module is shown in Fig. 8.

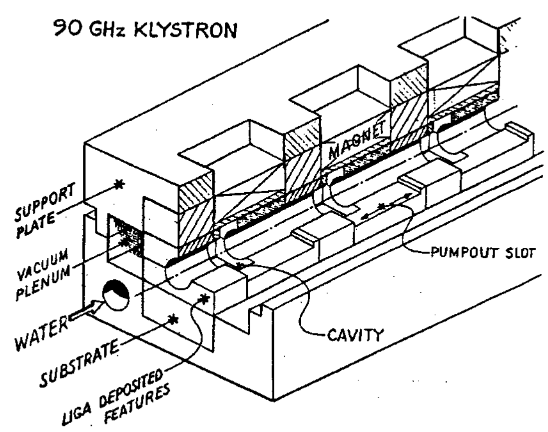


Fig. 7 RF section of a single-klystron module, showing construction details.

[3] "The Fabrication of Millimeter-Wavelength Accelerator Structures" P.J. Chou et al, SLAC-PUB 7339, Stanford Linear Accelerator Center.

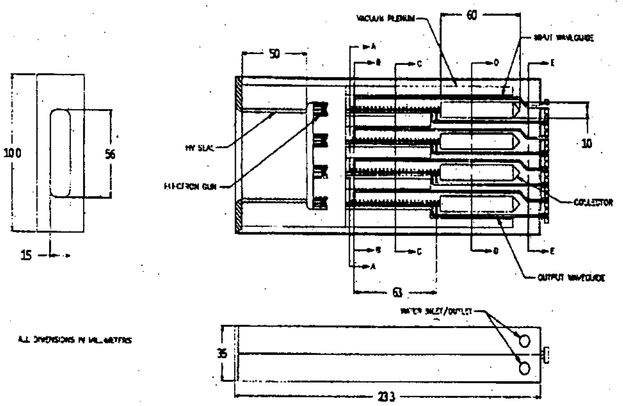


Fig. 8 Four-klystron module layout

The modest temperature increase at the output circuit indicated by the ANSYS simulation suggests that a higher duty factor is possible for the device. This can easily be established in actual test by increasing either the pulse length or the repetition rate. A modest, thermal detuning of the klystron output circuit will be compensated by the feedback "smart tube" feature and thus the duty indicated above can be doubled or tripled, with probably only a small decrease in peak power.

The bandwidth of the device is limited because of the high beam impedance. Percentage bandwidth can be improved with an increase in the R/Q of the output circuit. The four-section, extended-interaction circuit, used in the JAPANDISK simulation, (Q_{ext} = 270), will produce a bandwidth of approximately 0.4%, or about 350 MHz. This assumes that the gain cavities of the klystron are stagger-tuned and loaded, which is always possible in a klystron. For a wider bandwidth, more sections must be added to the output, or the Q_{ext} be reduced at the expense of a modest reduction in conversion efficiency. The latter approach is preferable because it will increase circuit efficiency and, therefore, there will not be a significant loss in overall efficiency for the device. Adding sections to the output circuit has a limit, set by potential monotron oscillations.

There is yet another available alternative for broadbanding, and one that is unique to the modular design approach. The four klystrons on the module can be designed to cover four separate bands for a total bandwidth of at least 1 per cent. They can be fed by a common TWT through a combining network, which pre-distorts individual klystron frequency responses to obtain a smooth, broadbanded, combined output. Combining can be effected as in the case of identical klystrons, since the quasi-optical scheme is good for at least a 5 percent bandwidth. In this case, the basic module (which can be paralleled with others) produces 125 kW, with a 1 GHz bandwidth, instead of 500 kW, with 350 MHz bandwidth.

Finally, we have prepared a paper design of a power supply and modulator that can power four modules as described above, for a total power output of 2 MW, and a duty factor of 0.1%. It is the size of a small file cabinet, with an estimated weight of 250 lbs. The design work was done to determine how onerous pulsed operation might be for applications where average or CW power is what is really needed. (Pulsed operation makes PPM focussing possible, and hence the module design itself depends on pulsing.) Fig. 9 shows a sketch of the complete subsystem, which involves a 15 kV charging supply and a thyratron-based PFN. Design details are available.

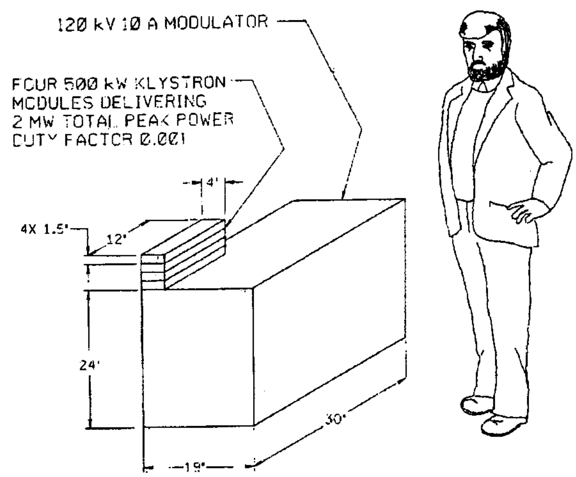


Fig. 9 2-MW, four-module "brick" with estimated modulator dimensions

Quasi-optical combining at the module or "brick" level is probably indicated for powering accelerators and radar transmitters. However, for other applications, such as "HPM," or ceramic sintering, where the objective is to simply concentrate power on an object, spatial power combining may be preferred. To avoid interference patterns at the target, individual klystrons can be phased randomly and the "brick" designed to form a mechanically steered beam.

In summary, a completely new approach to obtaining high power at W-band is proposed. It has been analyzed in detail and found to be valid. It is suitable for quantity production. Its success depends entirely on the availability of LIGA-fabricated cavities and magnetic polepieces for the individual klystrons. To this end, SLAC is working with Argonne National Laboratory and the Kernforchungszentrum Karlsruhe, Germany where the LIGA process originated.

7. ACKNOWLEDGEMENTS

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