A millimeter-wave klystron upconverter with a higher order mode output cavity

G. Burt, L. Zhang, D. A. Constable, H. Yin, C. J. Lingwood, W. He, C. Paoloni, and A. W. Cross

***Abstract*—Manufacturing of klystrons in the millimeter wave frequency range is challenging due to the small size of the cavities, and the ratio of the maximum gap voltage to the beam energy. The small dimensions make also difficult to produce devices with the output power required by a number of applications at millimeter wave, such as communications and spectroscopy. Operating with a higher order mode can be a potential solution, as a larger transverse size structure can be used. Unfortunately, high order mode cavities have a lower impedance than in fundamental mode. In this paper is proposed a novel solution to overcome the reduced impedance by utilizing an upconverter, where all cavities except the output cavity are designed to work in high order mode. To demonstrate the effectiveness of the approach, two klystron upconverters were designed. One has 6 cavities aiming to achieve a maximum output power of ∼90 W at 105 GHz. The second klystron upconverter was a simpler 3 cavity structure designed for quick prototype. Millimeter wave measurements of the three-cavity klystron upconverter are presented.**

klystron, upconverter, high-order mode.

I. INTRODUCTION

Millimeter-wave sources are required for many applications possible due to an atmospheric transmission window in the frequency range 90-110 GHz (W-band) [1]. At higher power level ($>$ 1 kW), extended-interaction klystrons [2] are commercially available. At lower power level ($<$ 1 W), there are solid state devices [3]. However, in the medium power range, there is a shortage of suitable sources at reasonably low cost.

The production of low-cost medium-power millimeter wave conventional klystrons around 100 GHz, is difficult due to three main reasons. Firstly, the size of parts of millimeter wave devices is in the range of only a few hundred microns, requiring expensive manufacturing processes. Secondly, as the sizes become smaller with increasing frequency, the beam diameter reduces accordingly, with a decrease of the maximum beam current, and hence a reduction of output power, proportional to $1/f^2$. Finally, the beam voltage has to be reduced accordingly as the gap voltage is limited by the small gap length. This translates in a reduced beam velocity, a smaller cavity gap and a significant decrease of the cavity impedance, resulting in reduced output power.

Klystrons working at a higher order mode can be a feasible solution to overcome the small size of the structure [4] When operating at a higher order mode, the dimensions can be larger, allowing easier manufacturing, as well as better electron beam transportation. Operating at a higher mode brings other issues, such as potential mode competition, higher sensitivity of the resonance frequencies to the klystron cavities and lower R/Q factor, as well as less efficient beam-wave coupling.

In this paper, klystron upconverters operating at W-band are proposed and designed, to explore their potential to foster the development of a new family of millimetre wave vacuum tube amplifiers. Balancing the issues mentioned above, only the output cavity of the klystron operates with a higher order (third harmonic) mode. The input and intermediate cavities still operate at the fundamental mode. There are a few benefits with this configuration: firstly, the use of lower frequency input and intermediate cavities with higher gap voltages and larger apertures not only increases the saturated power capability but also reduces the machining challenge; secondly, only the output cavity requires fine tuning to match the operating frequency, minimizing the difficulties on the circuit assembly and test. Finally, the ease of obtaining high power Ka-band input amplifiers reduces the need for high gain in the klystron, and thus, high input powers can be utilized.

II. HIGH-ORDER-MODE OUTPUT CAVITY

The klystron interaction structures were designed and simulated using the disk modeler AJDisk [5], with three and six cavity designs presented. Particle-in-cell (PIC) simulations using CST Particle Studio [6] of the three-cavity design are presented. The experimental setup of the three-cavity klystron upconverter, as well as the manufacture and millimeter wave measurements of the cavities are also reported.

A cuboid cavity with a flat re-entrant section was used as the klystron cavity [7]–[11]. The output cavity was chosen to operate at 105 GHz. Parameter sweeps are used to find the optimal re-entrant section dimensions to achieve a high R/Q for the higher order mode as well as keeping its resonance frequency at 105 GHz. The R/Q values and resonance frequencies as a function of re-entrant section width are shown in Fig. 1. In the simulations, the gap distance was chosen as 0.26 mm. The cavity height is around 3.6 mm and cavity length is 1.8 mm. The optimal value of the re-entrant section width is 2.46 mm.

The re-entrant cavity can be scaled to operate at other frequencies. The cavity geometry along with the electric field

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Graeme Burt (graeme.burt@cockcroft.ac.uk), David A. Constable (d.constable@lancaster.ac.uk), Chris J. Lingwood (c.lingwood@lancaster.ac.uk), and Claudio paoloni(c.paoloni@lancaster.ac.uk) are with Engineering Department, Lancaster University, Lancaster, LA1 4YW, United Kingdom, and Cockcroft Institute, Sci-Tech Daresbury, Warrington, WA4 4AD, United Kingdom. Liang Zhang (liang.zhang@strath.ac.uk), Huabi Yin (h.yin@strath.ac.uk), Wenlong He (w.he@strath.ac.uk), and Adrian W. Cross (a.w.cross@strath.ac.uk) are with Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, Scotland, UK.

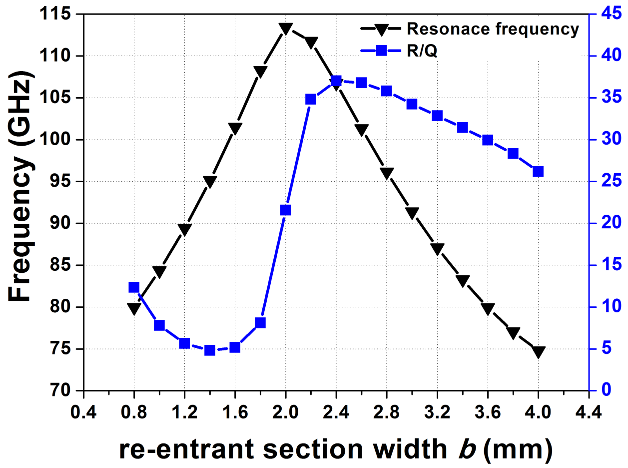
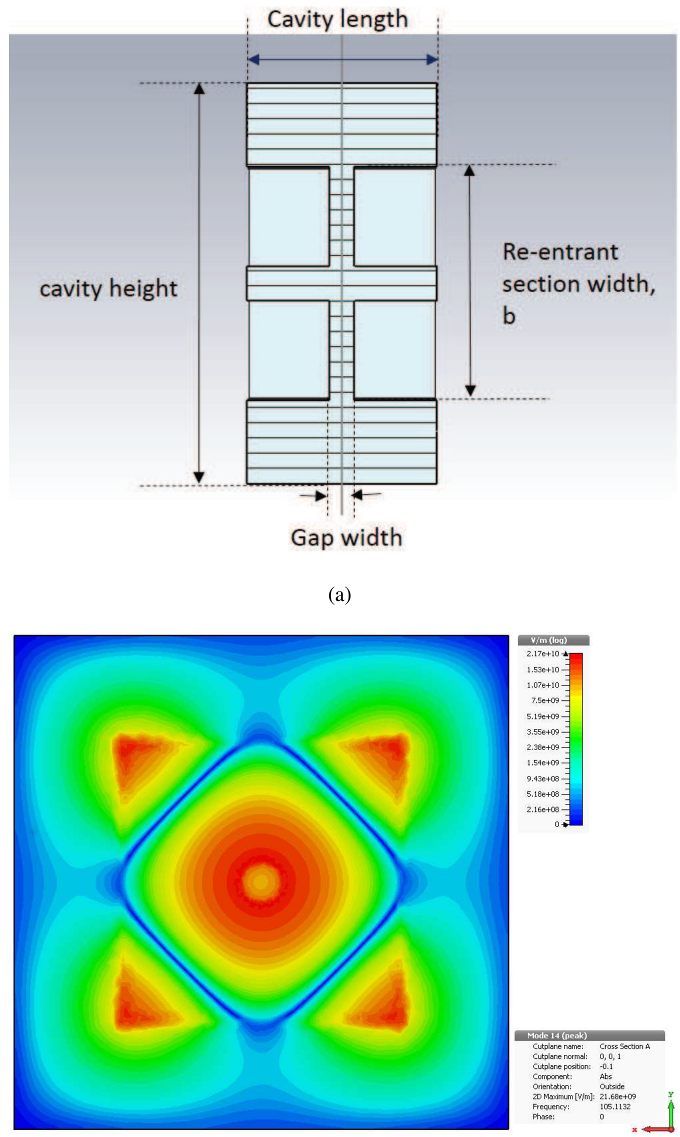


Fig. 1. R/Q as a function of re-entrant section width.



(a)

(b)

Fig. 2. Geometry of the re-entrant cavity (a) and Electric field pattern of the higher order mode in a cavity with a large re-entrant section (b).

pattern of the higher order mode is shown in Fig. 2. For a large re-entrant section with a small gap the fields become trapped in the gap as it behaves as an open-terminated radial waveguide. This mode has a significantly higher frequency, by a factor of 5, than the TM_{110} mode in the same cavity. From the simulations, the cavity with a large area re-entrant section is able to achieve higher R/Q. The maximum R/Q value of the TM_{330} mode in the large re-entrant cavity is about 3 times compared with the case without the re-entrant section, and about 7 times compared with a small re-entrant section in the same mode. It is because the large area, short gap re-entrant section is able to concentrate all the field in the gap between the re-entrant sections that results in an increase the R/Q value. As the re-entrant section width is increased the mode switches from a mode with fields everywhere to one with fields only between the re-entrant section at b=2.2 mm, significantly increasing the impedance. However, the maximum R/Q value of the TM_{330} mode is still about 5 times less than the TM_{110} mode working at the same frequency.

III. Design and Optimization of the Interaction Region

Two 105 GHz klystron upconverters were designed and optimized using AJDisk. The optimization process is automated using an evolutionary algorithm [12]. The first design features six cavities, to explore the potential of the klystron upconverter; the second consists of three cavities, with the aim of demonstrating the concept experimentally, using a 35 GHz input driver. In both cases, a beam voltage of 30 kV, current of 200 mA, and beam radius of 0.15 mm, was used, to match an existing thermionic cathode electron gun. At higher frequencies, the reduced gap voltage requires a lower beam voltage to achieve the same efficiency; however, the 30 kV beam voltage is still used due to the lower beam voltage significantly reducing the gap coupling factor and the efficiency.

For both upconverter designs, maximum gain was achieved by operating the intermediate cavities at frequencies close to 35 GHz, rather than utilizing any 105 GHz cavities. This is due to the higher shunt impedance resulting in increased bunching. Standard TM_{110} re-entrant cavities are used for the input and intermediate cavities, with ohmic Q factors of 1890, while the output uses the asymmetric output cavity design, with an R/Q of 12.9 Ohms, and ohmic Q of 1520. The external Q of the input and output cavities were optimized to be 615 and 1514, respectively; these values are higher than in conventional klystrons and is due to the need to increase the output cavity impedance because of low R/Q.

For an input power of $\sim$13.3 W, a saturated output power of 89 W is predicted for the 6 cavity upconverter, as shown in Fig. 3. The maximum efficiency is $\sim$1.5%. The transfer curve is not as smooth as a regular klystron because the output gap voltage is small compared to the beam voltage. As can be seen from Fig. 3, a maximum input power of $\sim$23 W exists for stable output at the third harmonic. In comparison a 6 cavity traditional klystron, but using the higher order mode cavities for every gap, was also optimised and was found to saturate at 34 Watts with a maximum gain of 11.46 dB. This demonstrates a factor of close to three improvement in saturated output power when the higher order mode cavities are implemented in an upconverter configuration as opposed to a traditional klystron configuration. We do not compare here to a klystron operating in the fundamental cavity mode as the cavities would be three times smaller increasing manufacturing costs significantly.

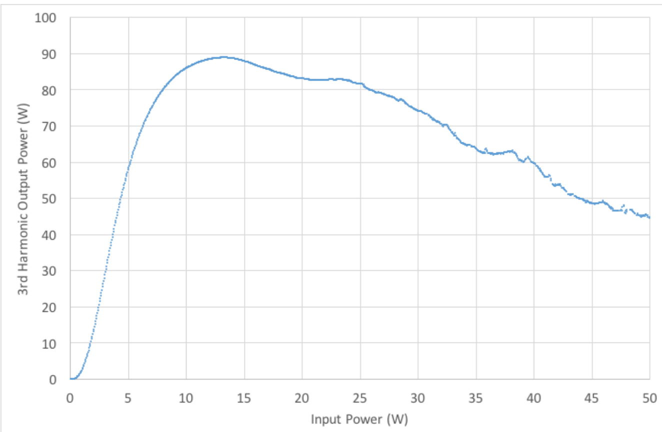
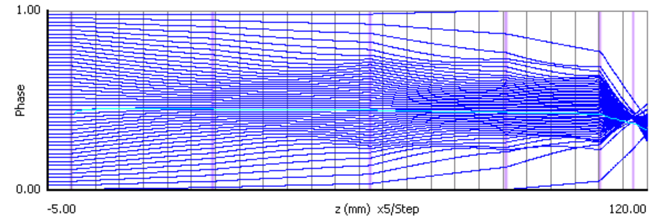


Fig. 3. Transfer curve of a six cavity klystron upconverter.

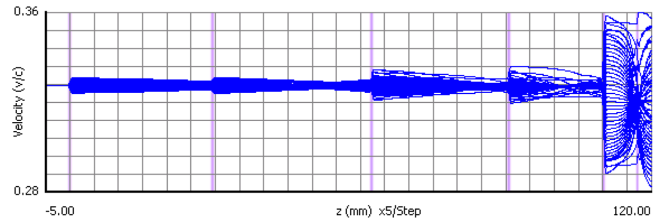
At peak efficiency, the klystron upconverter has a gain of 8.3 dB and is of length 117 mm. The beam behaviour from AJDisk is shown in Fig. 4(a). The effect of space charge forces can be observed within the core of the beam prior to the final cavity, resulting in the formation of three distinct beamlets at the penultimate cavity corresponding to the intended third harmonic output. The gain is significantly lower than for a traditional klystron due to the lower impedance of the output cavity and the lower third harmonic component in the beam current when compared to that of the first harmonic. The velocity spread in Fig. 4(b), shows there is not a significant deceleration of the electrons after the output cavity, as is common in traditional klystrons. This is in keeping with the inherent lower efficiency of the upconverter.

For larger input powers, the phase-space behaviour of the device becomes chaotic, with electron trajectories crossing prior to the output cavity. The electron trajectories can be seen to cross over in the drift region between the third and fourth cavities, which is then continued in successive drift regions. At the output cavity, the bunch is significantly distorted, resulting in the decreased output power. In comparison, for the case of maximum efficiency, no crossing in the electron trajectories is observed.

A number of simulations were performed with a spread of cavity frequencies to study the effect of the tolerances. The effect on the third harmonic output power, with a 13.3 W input power was assessed for various error spreads. The results show that the frequencies need to be within 0.075% of the design values to achieve over 45 W (-3 dB) which is consistent with the 0.075% bandwidth of the intermediate cavities.



(a)



(b)

Fig. 4. Applegate diagram (a) and velocity spread (b) in the 105 GHz klystron upconverter, for an input power of 13.3 W.

A simple 3 cavity klystron was also designed and will be experimentally studied. To achieve fast prototyping, the operating frequency was chosen as 105 GHz to match the available input driving source operating at 35 GHz. The beam current was 200 mA to fit a previous designed thermionic electron gun.

AJDisk predicts that highest output power occurs when the frequency of the intermediate cavity is 50 MHz higher than the input cavity. While the lack of intermediate cavities reduces the bunching, an output power of 58 W was predicted for 10 W input power. There is a large distance between the input and intermediate cavity to maximize the bunching. The intermediate cavity has a higher gap voltage than the input cavity so a shorter distance is then required to the output cavity. The applegate diagram of the three cavity klystron upconverter is shown in Fig. 5.

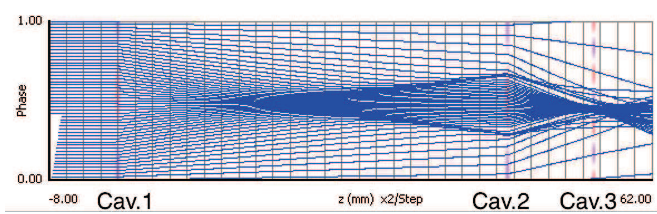


Fig. 5. The three cavity 105 GHz klystron upconverter applegate diagram from AJDisk.

Self-consistent particle-in-cell (PIC) simulations of the three-cavity 105 GHz klystron were performed in CST Particle Studio. The overall geometry is shown in Fig. 6. The simulation was run for 40 ns and the output power, gap voltages as well as the beam phase-space were monitored. The intermediate and output cavities were found to have gap voltages of approximately 4 kV and 0.7 kV respectively. The output power was simulated to be 40 W which is also in relatively good agreement with the 58 W predicted by the

AJDisk.

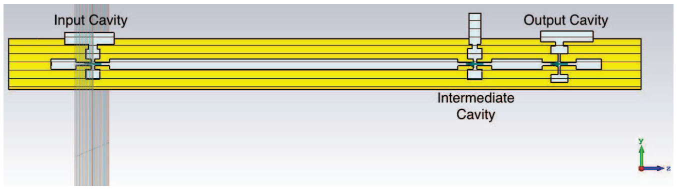
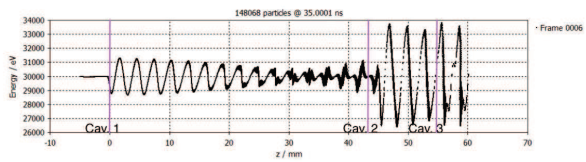
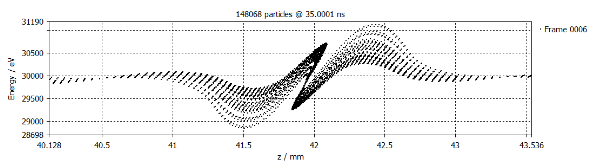


Fig. 6. The whole structure of the 105 GHz klystron upconverter.

The longitudinal phase-space of the beam at each cavity are shown in Fig. 7. The space charge reduces the velocity spread between the input cavity and the intermediate cavity and shows some distortion of the bunch in the intermediate cavity. Good bunching is seen in the output gap with a bunch width of around 0.1 mm.



(a)



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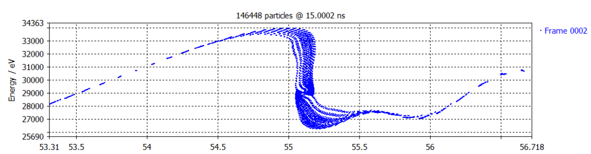

(c)

Fig. 7. Longitudinal phase space in the 105 GHz klystron upconverter (a) and zoomed in for the intermediate cavity (b) and output cavity (c).

IV. EXPERIMENTAL STUDY OF THE KLYSTRON UPCONVERTER

The thermionic electron gun used for the klystron upconverter is modified from an existing Pierce type gun using Vaughan's synthesis [13]. The magnetic field use to confine the electron beam was generated by a water cooled solenoid with a maximum magnetic field $\sim$2.0 T [14]. The beam trajectories of the electron gun were simulated by CST Particle Studio, as shown in Fig. 8. The beam parameters satisfy the requirement for the experiments.

The manufactory of the klystron cavities at high frequency is very challenging. The W-band (105 GHz) upconverter cavity was firstly machined and built by assembling a few parts together to form the reentrance cavity as well as the output coupler. Each part was machined by wire cutting method. The parts and the assembled structure are shown in Fig. 9.

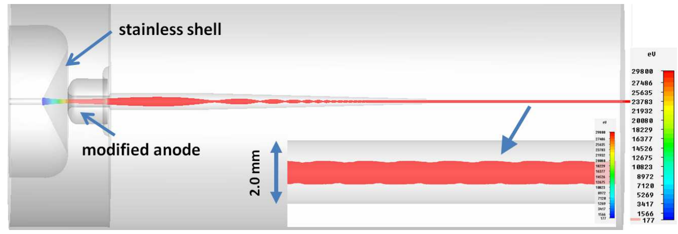

Fig. 8. The beam trajectories simulated by CST Particle Studio.

The vector network analyzer (VNA) measurement shows the resonance frequency is close to the designed value of 105 GHz with a Q factor of 90, as shown in Fig. 10. And it can be slightly tuned by changing the cavity gap distance through tightening or unscrewing the screws. However, it is not practical to manufacture the whole klystron structure using this method, as it will involve with too many assembly pieces which can lead to leakage losses as well as contact resistance. The Ohmic Q of the cavity is only 180 significantly lower than the predicted 8346. The results also show a matched coupler meaning that the external Q must also be 180 rather than 990. This suggest that the signal is coupling in and out of the structure via the gaps, loading the cavity and the ohmic Q is actually ohmic plus leakage losses. The alignment will become a huge problem too.

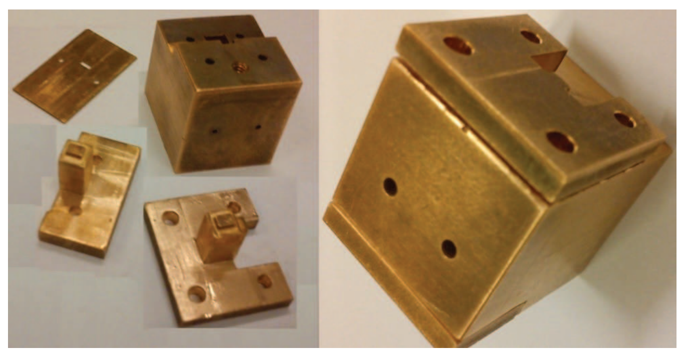

Fig. 9. Wire cutting and assembly of the klystron cavity.

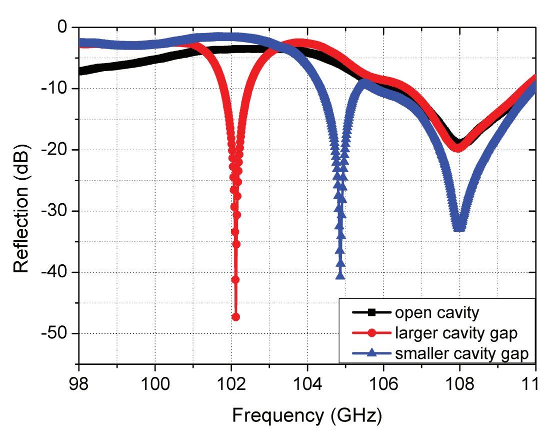

Fig. 10. Measurement of the output cavity manufactured by wire EDM.

The 3D printing technique [15] is an additive manufacturing process, allowing fabrication of virtually any 3D object from a digital model. In recent years the significant progress in tolerances and availability of numerous materials make additive manufacturing suitable for microwave structures.In this paper it has been adopted for making the cavity structures. Silver was chosen due to its high conductivity, as well as less chance to poison the thermionic cathode, although it has the disadvantage of bigger gas leakage rate. The fabrication tolerance is about ± 0.15 mm at present, but it may be possible to tune the frequency with tuning pins to account for this.

The whole klystron structure, including the input and output couplers, cavities, beam tunnel and beam collector, is built in two halves. The small beam tunnel diameter of 0.2 mm and length of 60 mm, are at the 3D printing tolerance. The printed klystron structure is shown in Fig. 11a. By printing in only two halves the leakage losses which limited the measurement of the copper structure would be significantly reduced. The gaps shown in the figures are placed perpendicular to the magnetic fields, which loop around the nose cones, preventing coupling to the gap. However the dimensions of the output cavity gap is difficult to achieve by 3D printing. After 3D printing the wire cutting method was used to create the gap with the proper dimenisons, as shown in Fig. 11b. A well known problem of the printed structure is the surface finish. Although further polishing can help to improve the surface finish, it is difficult to reach the inner surface of the klystron cavities. That results in the cavities having lower Q factors than intended.

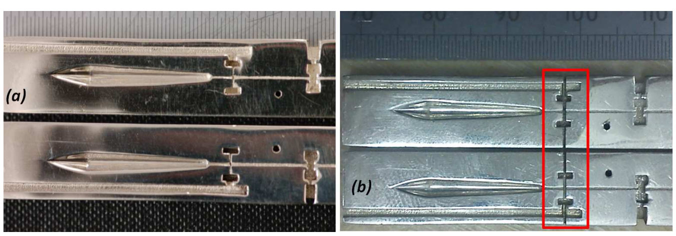

Fig. 11. klystron structures manufactured by 3D printing technology (a) and fixed by wire cutting method (b).

The electrical properties of the klystron cavities were measured using a VNA. The resonance frequency of the input cavity is very close to the designed value. However, the measured Q loaded factors are much lower than designed. This is due to the cavities surface roughness and problems in manufacturing the coupler, likely caused in the polishing stage. The coupler seems to be matched suggesting that again leakage may be a key issue.

The output cavity operates at a high order mode, and its performance is much more sensitive to the machining tolerance. The measured resonance frequency is 104.76 GHz, in very good agreement with the designed value of 105 GHz. The measured loaded Q factor is about 213.8. The resonance frequency can be slightly tuned by inserting a thin copper foil into the wire-cutting slots. The resonance frequency after tuning is 104.91 GHz, however the Q factor becomes even smaller. Table 1 shows the resonance frequencies and Q factors of the klystron cavities, both simulated in CST Microwave Studio and measured experimentally.

Combining the 3D printing technology with conventional machining technology, it is possible to manufacture the klystron structure with reasonable accuracy. The resonance frequencies of the cavities are relatively close to the designed values. However, the surface roughness has to be improved to achieve high Q factors. This would be important for many vacuum electronic circuits, and especially so for klystrons. Leakage of radiation may also occur due to a slight mismatch between both halves of the assembly. This would have also affected the incorrect Q values. However, due to the rapid development of the 3D printing technology, the machining tolerance is improving and more metal materials are printable. The great advantage is a very low fabrication cost.

TABLE I
SIMULATED AND MEASURED RESONANCE FREQUENCIES AND Q FACTORS OF THE KLYSTRON CAVITIES

Cavities	Frequency (GHz)		Loaded Q factor	
	Simulated	Measured	Simulated	Measured
Input	35.00	35.09	576	82.7
Intermediate	35.05	35.40	2698	85.4
Output (AM)	105.00	104.91	596	213.8
Output (wire)	105.00	105.00	1844	90
	Ohmic Q factor		External Q factor	
	Simulated	Measured	Simulated	Measured
Input	2172	164.4	783	164.4
Intermediate	2870	170.8	44984	170.8
Output (AM)	1498	427.6	990	427.6
Output (wire)	2368	180	990	180

V. CONCLUSIONS

In this paper, a klystron upconverter operating at 105 GHz with the output cavity operating at higher order mode are investigated to achieve medium-power, low-cost microwave radiation. A maximum power of 89 W is predicted from a 6-cavity 105 GHz klystron upconverter, with beam voltage of 30 kV and current 200 mA.

A 3-cavity proof-of-principle klystron upconverter was also designed, manufactured and tested using a Vector Network Analyser (VNA) and experimentally studied. The 3D printing method and the wire cutting technology were used to manufacture the klystron structure. The resonance frequencies and Q factors of the cavities were measured by the VNA. The resonance frequencies of the cavities are all relatively close to the designed values while the Q factors are much smaller than designed values due to either their poor surface roughness or leakage through gaps. However, benefiting from the rapid development of the 3D printing technology, it may be possible to achieve a better surface roughness in the future.

The novel klystron upconverter structure permits the use of low impedance structures with larger dimensions to produce output powers with full scalability and relative ease of fabrication. A standard klystron using the low impedance cavities would in comparison produce significantly lower powers by almost a factor of three, and a upconverter or klystron with a fundamental mode in the output cavity would require significantly smaller structures significantly increasing costs. By combining both concepts we achieve a signifantly improved performance.

Acknowledgments

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