Measurement of 30kW output from a W-band source constructed by additive manufacturing

A. R. Phipps, A. J. MacLachlan, C. W. Robertson, L. Zhang, A. W. Cross, and A. D. R. Phelps
Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, Scotland, UK
a.d.r.phelps@strath.ac.uk

Abstract—**Experimental results from the operation of an electron beam driven, mm-wave, vacuum electronic source are reported. The aim of this work is to create improved electron-beam-driven, vacuum electronic mm-wave and sub-THz sources by exploiting dispersion-engineering. Dispersion-engineered structures can be manufactured by several techniques and in this work additive manufacturing has proven to be quick, reliable and cost-effective.**

Keywords — W-band source; mm-wave source; additive manufacturing; periodic structures.

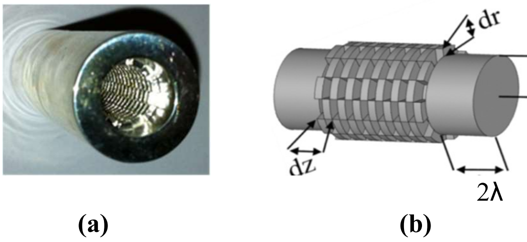
I. INTRODUCTION

Smart dispersion engineering is having a positive impact on mm-wave source research, leading to improved high-power coherent sources [1-6]. Two dimensional periodic surface lattices (PSLs) [3,4] can be created by manufacturing shallow periodic perturbations on the inner surface of a hollow electrically conducting cylinder. Such 2D PSLs can be used for several applications exploiting different physical phenomena. A dispersion relation describing the coupling of the volume and surface fields inside a 2D PSL of cylindrical topology was derived by Konoplev et al. [5]. Under certain conditions, when driven by a suitable electron beam this provides a coherent source of electromagnetic radiation. These cylindrical 2D PSLs show significant potential for use in electron-beam-driven high power, coherent sources [6].

The cylindrical PSL structures need to be compatible with vacuum conditions and the use of energetic electron beams, while also providing the required boundary conditions for the electromagnetic fields. Manufacturing the cylindrical PSLs out of a suitable metal usually provides a good vacuum envelope and the electrical conductivity allows electrical charges impacting on the surfaces to be conducted away. A technique that we have previously employed to manufacture dispersion-engineered structures involves milling sinusoidal perturbations on the outer wall of an aluminium former and then electrodepositing copper directly onto the surface. The aluminium was then dissolved in a strong alkaline solution, leaving the copper structure with the perturbations on the inner surface. However, for the source reported here additive manufacturing (or 3D printing) [7] has been used for the construction of the cylindrical PSL.

II. RESULTS

The PSL to be used in the 'hot' experiment was constructed using a high resolution 3D printing process that included the injection moulding of a silver chromium alloy. 3D printing, originally developed in the mid 1980's, offers the possibility of producing objects that have resolutions on the 10's of microns scale. 3D printing is an additive process by which consecutive layers in the x-z plane are deposited sequentially in the +ve y direction (upwards), resulting in a high resolution (approximately ± 15 microns) wax model that is then used in a casting process that ultimately results in the silver alloy (80 to 90) GHz 2D PSL, seen in Fig. 1. The printing process follows the pattern in a given CAD input file, usually in the STL (Sereolithograph) file format where every face is built from a series of interconnected triangles represented by 3 separate 32-bit floating-point Cartesian coordinates. More often now the new X3D file format is implemented which incorporates the XML programming interface and further enhancements over its predecessors. The design is sliced into digital layers so that that a curve is 'approximated' by many square-sided slices, with the thickness of each layer representing the resolution of that particular 3D printing process. Fig. 1(a) demonstrates the result of the 3D printing process with a complete 2D PSL made from a silver alloy of Ag = 92.5 % and Cu = 7.5 %. Fig. 1(a) is a photograph of a cylindrical silver-chromium alloy 2D periodic surface lattice, cast using the primary mandrel created by additive manufacturing. The virtual schematic of the mandrel is seen in Fig. 1(b) which shows the relevant dimensional parameters. The dimensional errors achievable with 3D printing are projected to decrease over time as the technology develops.



(a) **(b)**

Fig. 1. (a) Interaction structure consisting of a cylindrical silver-chromium alloy 2D periodic surface lattice (b) Cylindrical CAD virtual mandrel that when constructed using additive manufacturing provided the mold for casting the cylindrical 2D PSL.

Fig 2 shows a schematic of the experimental configuration of the interaction region, with the electron beam passing through the cylindrical PSL and the parameters of the PSL are shown in Table 1. Ideally an annular electron beam positioned at a radius close to the periodic lattice structure should be used [8,9]. A photograph of the complete assembled experimental system is shown in Fig. 3.

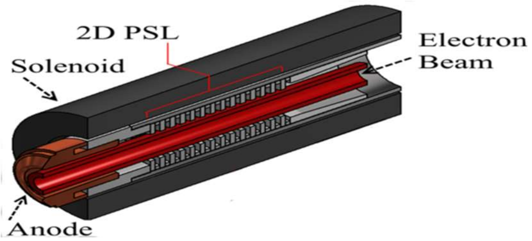


Fig. 2. Configuration of the cylindrical periodic surface lattice and annular electron beam guided by the solenoidal magnetic field.

Parameter	Symbol	Value
Longitudinal Period	dz	1.6 mm
Azimuthal Variations	m	7
Number of Longitudinal Periods	n	16
Amplitude	dr	0.8 mm
Amplitude (Peak-to-Peak)	dr (pk-pk)	1.6mm
Inner Radius of input and output waveguide	r	4 mm
Minimum radius of perturbation (ID)	r_{min}	3.6 mm
Mean radius	r_0	4.4 mm
Maximum radius of perturbation (OD)	r_{max}	5.2 mm

Table 1. The parameters of the 2D cylindrical PSL structure

Fig. 3 The complete assembled experimental system used for the measurements of the millimetre-wave output.

Measurements of the voltage and current waveforms of the electron beam are shown in Fig. 4. To measure the amplitude of the output radiation field from the source, a W-band (75 to 110 GHz) Flann rectifying crystal detector with a rotary vane W-band attenuator and Flann 15 dB horn were used located at a distance of 0.6 m from the output window. Cut-off filters were in the form of different diameter hollow cylindrical waveguides situated between the receiving horn and the detector. The output radiation from this oscillator measured through the series of high-pass filters is shown in Fig 5.

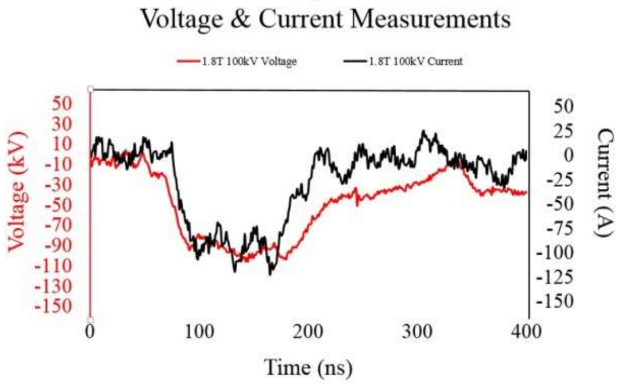


Fig. 4. Pulsed voltage and current waveforms.

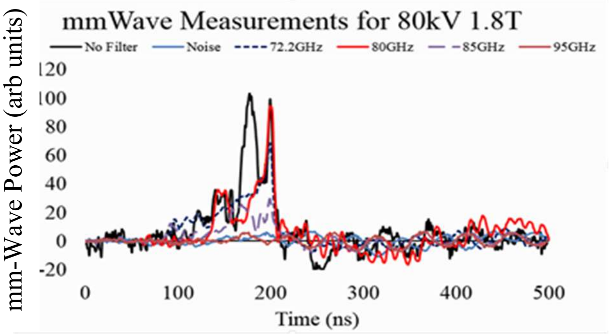


Fig. 5. Measured mm-wave output after passing through a series of high-pass filters.

In the first experimental measurements of the output radiation from this oscillator, the frequency, determined using the set of cut-off filters was found to be in the range 80 to 85 GHz. The peak output power has been measured as ~30kW. In future work it is proposed to make a more precise frequency measurement using a local oscillator and conventional mixer technique. In this initial experiment it is recognized that the amplitude of the perturbations employed is much larger than the amplitude corresponding to the description "shallow perturbations". It is proposed to use a range of smaller amplitude perturbations in future experiments. Also it is planned to improve the electron beam transport and electron beam radial position to provide a much higher electronic efficiency than the relatively low ~1% efficiency observed in these initial experimental measurements.

III. CONCLUSIONS

Cylindrical 2D PSL structures for an electron-beam-driven mm-wave oscillator have been successfully prototyped using additive manufacturing to create the primary mold. This additive manufacturing method that has already been successfully used by others in lower frequency microwave sources [10] has been shown in recently reported work by Phipps et al. [11] and in our present work to be capable of prototyping dispersive structures and complex components for sources in the (W-band) mm-wave range. At present the resolution obtainable with additive manufacturing probably limits the upper frequency achievable to approximately the frequency of the experimental mm-wave source reported here. Although much of the reduced experimentally observed efficiency in the present device is due to the electron beam radial profile not achieving the ideal profile used in numerical simulations, some of the lowered efficiency is considered to be due to the limited precision with which the periodic structures can be constructed using additive manufacturing. If, in future, the resolution obtainable with this manufacturing technique improves, correspondingly higher frequency sources could be constructed using this manufacturing method.

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