ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research B xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Electron beam excitation of coherent sub-terahertz radiation in periodic structures manufactured by 3D printing

A.R. Phipps [a], A.J. MacLachlan [a], C.W. Robertson [a], L. Zhang [a], I.V. Konoplev [b], A.W. Cross [a], A.D.R. Phelps [a],*

[a] *Department of Physics, SUPA, University of Strathclyde, Glasgow G4 0NG, UK*
[b] *John Adams Institute, Department of Physics, University of Oxford, Oxford OX1 3RH, UK*

ARTICLE INFO

Article history:
Received 28 November 2016
Received in revised form 14 March 2017
Accepted 15 March 2017
Available online xxxx

Keywords:
Periodic structures
Electron beam
Sub-terahertz radiation
3D printing

ABSTRACT

For the creation of novel coherent sub-THz sources excited by electron beams there is a requirement to manufacture intricate periodic structures to produce and radiate electromagnetic fields. The specification and the measured performance is reported of a periodic structure constructed by additive manufacturing and used successfully in an electron beam driven sub-THz radiation source. Additive manufacturing, or "3D printing", is promising to be quick and cost-effective for prototyping these periodic structures.

1. Introduction

Additive manufacturing [1], or "3D printing", is a quick and cost-effective method for prototyping periodic structures. In the present work the technical performance of a periodic structure manufactured by 3D printing is reported. The structure reported here has been used in an electron beam driven radiation source that has produced mm-wave output in the 80–90 GHz region. French and Shiffler [2] have reported successfully creating a powerful microwave source in the 4–5 GHz range using 3D printing. Such structures are of great interest because the application of smart electromagnetic designs is having a positive impact on research leading to improved high-power coherent microwave, mm-wave and sub-THz electron-beam-driven sources including both fast wave and slow wave interactions [3–12]. Macor et al. [13] have demonstrated the capability of constructing a variety of passive components for millimetre to terahertz electromagnetic waves, using metal-coated polymers shaped by 3D stereolithography, which uses essentially the same methodology as additive manufacturing, or 3D printing.

One of the motivations for our present research is to explore the range of source frequencies for which 3D printing manufacturing methods for active components can be usefully applied. The dimensional precision that 3D printing can achieve is tending to improve, which should lead to the widening of the frequency range for which this constructional method of producing complex microwave/mm-wave source structures can be applied.

2. Two dimensional (2D) periodic surface lattice (PSL)

The 2D PSLs [14] can be created by manufacturing shallow periodic perturbations on the inner surface of a hollow electrically conducting cylinder. 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 good electrical conductivity allows conduction away of any electrical charges impacting on the surfaces. A good thermal conductivity coefficient is another property that metals tend to possess and is helpful for PSLs intended for use in high power sources.

The interactions between charged particle beams and periodic structures, that can be one, two, or three dimensional provide a very fruitful research area [15,16]. Structures used to excite Smith-Purcell radiation share many of the same modeling [16], constructional and measurement challenges as the present work. Periodic structures that produce electromagnetic radiation can be used for several applications that exploit a variety of physical phenomena [17]. 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. [18]. Under certain conditions, when driven by a suitable electron beam this structure can support

---

* Corresponding author.
E-mail address: a.d.r.phelps@strath.ac.uk (A.D.R. Phelps).

http://dx.doi.org/10.1016/j.nimb.2017.03.093
0168-583X/

Please cite this article in press as: A.R. Phipps et al., Electron beam excitation of coherent sub-terahertz radiation in periodic structures manufactured by 3D printing, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.03.093

a Cherenkov instability that provides a coherent source of electromagnetic radiation [19].

The cylindrical 2D periodic structure can be described by Eq. (1)

$$r = r_0 + \Delta r \cos(kz + m\varphi) \tag{1}$$

where r_0 is the radius of the unperturbed waveguide, Δr is the corrugation depth, $k_z = 2\pi/d_z$, d_z is the period of the corrugation over the z – coordinate and m is the number of variations of the corrugation over the azimuthal coordinate.

3. 3D printing of cylindrical 2D PSL

Periodic structures in cylindrical geometry have been successfully prototyped using 3D printing to create a primary mould, which has then been used to cast successfully a metallic cylindrical PSL to form the interaction cavity for a novel sub-THz source.

The 3D printing process is a two stage process. The first stage involves creating a wax former to the 10's of microns scale and then using this former to create a mould for the component where the silver – chromium molten alloy is deposited, with the resulting part having a resolution of ±125 μm. 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 positive y direction (upwards), resulting in a high resolution (approximately ± 15 μm) wax model that is then used in a casting process that ultimately results in the silver alloy (80–90) GHz 2D PSL, seen in the image below. The printing process follows the pattern in a given CAD input file, usually in the STL (Stereolithograph) 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 a curve is 'approximated' by many square sided slices, with the thickness of each layer representing the resolution of that particular 3D printing process.

Although this resolution is not at present as high as can be achieved with a precision milling process, it does have the advantage of taking a lot less time to achieve the finished structure and in conjunction with the lower cost, the 3D printing process is more efficient overall.

A 2D PSL structure with parameters as shown in Table 1 was manufactured for electromagnetic measurements using a VNA and for subsequent use in electron beam experiments. Images of the cylindrical 2D PSL made using 3D printing are shown in Fig. 2.

The 2D cylindrical PSL shown in Fig. 2 is made from a silver alloy of 92.5% silver and 7.5% chromium.

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

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)	1.6 mm
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

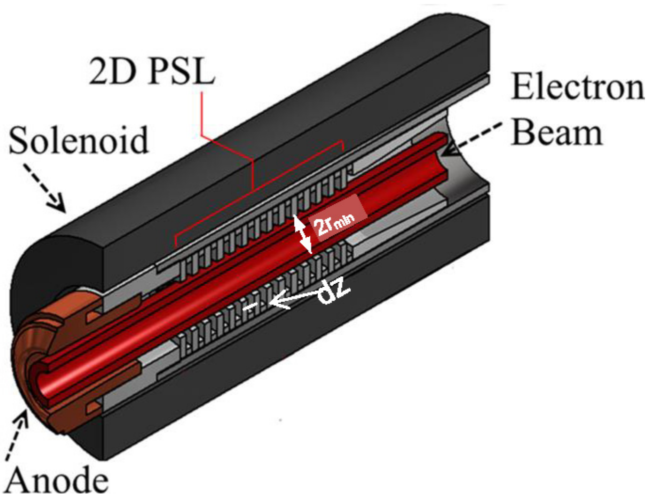

Fig. 1. Configuration of the cylindrical periodic surface lattice and annular electron beam guided by the solenoidal magnetic field.

Fig. 2. Cylindrical PSL manufactured using 3D printing.

4. Electromagnetic measurement of the cylindrical 2D PSL

Measurements, made using a vector network analyser, of the electromagnetic properties of the cylindrical PSL manufactured by these methods, are compared with simulations made using the software CST Microwave Studio.

Using a serpentine co-axial mode converter operating in G-band (140–220 GHz) a $TM_{0,n}$ wave was launched into the high contrast (1.6 mm deep corrugation) 2D PSL with the transmission measured over the 140–220 GHz frequency range using an Anritsu ME7808B Broadband Lightening Vector Network Analyzer VNA with two transmit and receive SM5952 140–220 GHz OML extender heads. The $TM_{0,1}$ mode from the circular serpentine mode converter becomes a TEM mode in the co-axial conical horn which then launches a $TM_{0,n}$ mode in the cylindrical 3D printed 2D PSL.

When testing the structure using the VNA the interaction produces an electromagnetic wave that interacts with the 1.6 mm longitudinal period giving a response in G-band resulting in a resonance at 187.7 GHz, as shown in Fig. 3 showing the millimetre wave transmission as a function of frequency. The electromagnetic wave when interacting with the 3.5 mm azimuthal period will give

Please cite this article in press as: A.R. Phipps et al., Electron beam excitation of coherent sub-terahertz radiation in periodic structures manufactured by 3D printing, Nucl. Instr. Meth. B (2017), http://dx.doi.org/10.1016/j.nimb.2017.03.093