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Design of Photonic Crystal Klystrons

DESIGN OF PHOTONIC CRYSTAL KLYSTRONS

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Abstract

2D Photonic crystals (PC) with defects can act as standing-wave resonators, which offer benefit of high mode selectivity for building novel RF sources [1]. We introduce our work on designing two-cavity single-beam and multi-beam klystrons using triangular lattice metallic PCs. We present the cold test results of the stub-coupled single-beam structure, which show that at resonance a very low reflection can be obtained, and the waves are well confined. We also present bead-pull measurement results of field strengths in the defect, using modified perturbation equation for small unit dielectric cylinder, which are in very good agreement to numerical results. A 6-beam klystron cavity is designed as a 6-coupled-defect structure with a central stub, which only couples to the in-phase mode at the lowest frequency. Finally, we present a feasibility discussion of using this multi-defect PC structure to construct an integrated klystron-accelerator cavity, along with numerical results showing a peak acceleration field of 22MV/m can be achieved.

INTRODUCTION

A 2D PC is a periodic lattice of materials, which over certain frequency ranges prevent EM waves from propagating through. A PC resonator can be designed by creating a defect in the lattice, which confines EM waves specifically with frequencies in the bandgap. These PC-type resonators offer many advantages over conventional pillbox cavities by propagating away the higher order modes (HOMs) from the PC lattice [1], and have been theoretically and experimentally verified to be feasible in applications of particle accelerators by the authors of [2]. Besides that, the exemption of HOMs in wakefields (WFs) excited by electron beams in PCs also provides the opportunity of building novel compact RF sources at frequencies of X-band or even higher [1]. In this paper we present our investigation of using PCs to build compact klystron-type RF sources, as well as a PC-based integrated klystron-accelerator structure.

SINGLE-BEAM PC KLYSTRON CAVITIES

Our first single-beam PC structure was made by arranging copper rods of 2mm radius into a triangular lattice of centre-to-centre rod spacing (lattice constant) 12.5mm, in-between two parallel copper plates separated by 3.7mm. This lattice gives a band-diagram shown in Figure 1 (d).

Frequency Characteristics

In the copper structure a rod was removed from the lattice to create a defect for EM field confinement and beam transit, and the rod two-lattice-constant away from the defect was replaced by an SMA stub, which couples EM waves into the structure, as shown in Figure 1 (a). We measured the reflection from 2 to 18GHz using an Agilent E8362B network analyser. The results in Figure 1 (d) show there is a weak mode associated with the stub coupler at 8.93GHz, and the main resonance occurred at 9.466GHz at very low reflection coefficient 0.006 (critical coupling), well matches the prediction from Eigenmode simulation using CST Microwave Studio [3]. The reflection measurement also shows that the passband starts from 12.98GHz, which agrees well with the band-diagram calculated from BandSOLVE (Figure 1 (d)) [4]. The dipole mode predicted by Microwave Studio lies in the passband (Figure 1 (c)). We also measured the power leakage outside the structure. Significant power leakage can only be detected at passband, which means EM waves are not able to be confined at these frequencies. There was no power detected in the bandgap, i.e. waves coupled into the structure at the main resonance, which lies in this region, must be efficiently confined inside the structure. The results are also shown in Figure 1 (d), for comparison with reflection curve and band-diagram.

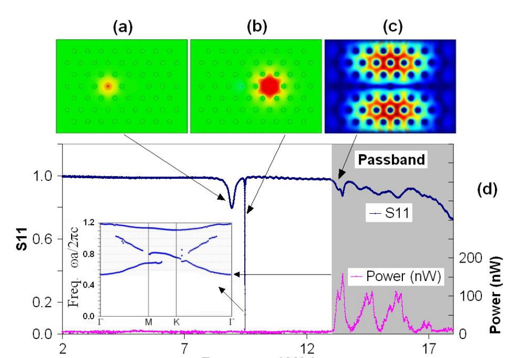

Figure 1: (a). Weak field associated with stub coupler. (b). Monopole mode confined at defect region. (c). Dipole mode at passband. (d). Measured reflection and power leakage compared with band-diagram.

Measurement of Electric Field Strength

Having verified the frequency response of the PC structure, we also measured the longitudinal electric field distribution at resonance, along the axis of the defect, by performing the bead-pull measurement based on cavity perturbation theory [4]. The bead used was a small unit cylinder

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of Dynallox96 (96% Al2O3) with $\epsilon_r = 9.4$, both the diameter and height of which were 790μm, tight up by a Nylon fishing line of 80μm diameter, as shown in Figure 2. As there is no existing perturbation equation for unit dielectric cylinder that directly applies to the calculation of electric field strengths, we rewrite the equation in terms of the dielectric polarisability α, which describes how a dielectric is polarised in electric field:

$$\frac{\Delta\omega}{\omega_0} = \frac{\epsilon_0(\epsilon_r - 1)\,|E_z|^2}{4U_0} V_{bead} \cdot \alpha \qquad (1)$$

In Equation (1), ω_0 is the angular resonant frequency of un-perturbed structure; $\Delta\omega$ is the difference of frequencies before and after perturbation; U_0 is the total energy stored at resonance and V_{bead} is the bead volume. α of a unit dielectric cylinder has been numerically estimated by Jukka Venermo etc. in [6]. Using this approach, the magnitude of axial electric field along the defect axis, Ez, being normalised to 1W power, has been calculated from Equation (1) and plotted in Figure 2. Comparison with simulation results from Microwave Studio shows a very good agreement with difference less than 2%.

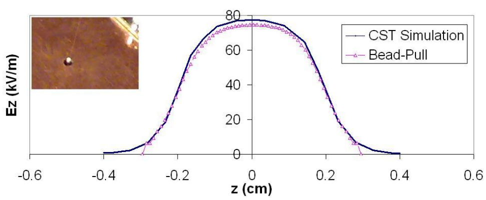

Figure 2: Bead-pull measurement of field strength compared with CST simulation results.

A Two-Cavity Single-Beam PC Klystron

Using the field in Figure 2 to velocity-modulate a 20kV 0.5mA electron beam, gives the bunching effect shown in Figure 3 (a), which is modelled using the numerical code VORPAL [7]. Figure 3 (a) shows that clear bunches are formed at 12cm drift distance, where a second PC structure can be located to extract energy from the beam.

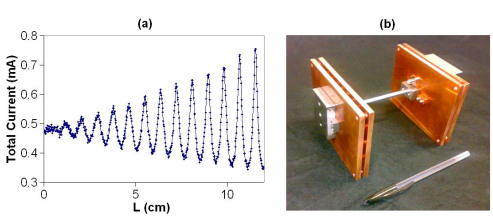

Figure 3: (a). Electron beam bunching. (b). A two-cavity single-beam device.

The lattice of the extraction structure is very close to the first one, except the stub coupler is placed next to the defect. This gives a loaded Q of 820 at 9.466GHz. Our constructed two-cavity single-beam device is shown in Figure 3 (b).

6-BEAM PC KLYSTRON CAVITIES

PCs also give opportunities for building multi-beam devices by creating multiple defects. The simplest multi-defect structure can be created is a 6-coupled-defect structure (Figure 4 (a)). The wave patterns existing in this type of structures and their application have been previously reviewed by A. Smirnov etc. in [8-11]. In this paper we present our estimation of the physical excitation of a 6-defect structure by bunched electrons, and discuss its feasibility in application of multi-beam klystrons.

In our 6-defect structure of lattice r/a=1.5mm/11.5mm, we first scanned the eigenmodes using MEEP 2D code, which shows all the four (monopole, dipole, quadruple, sextuple) modes exist in the structure, as shown in Figure 4 (a)-(d). The two dipole and quadruple modes in [8] merge into a single mode respectively.

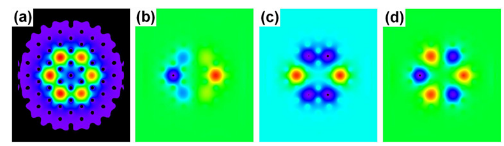

Figure 4: Field patterns in 6-defect structure: (a). Monopole mode at 9.37GHz. (b). Dipole mode at 9.61GHz. (c). Quadruple mode at 10.08 GHz. (d). Sextuple mode at 10.35GHz.

The excitation of these modes by particles was verified from VORPAL 3D PIC simulation. By sending a single bunch of electrons (which contains all the frequency components) into one defect, all the four modes can be excited, as shown in Figure 5 (a). However, if each of the defects is loaded with an electron bunch synchronously, only the monopole mode can be excited; all HOMs are suppressed as they are not in-phase at all the defects (Figure 5 (b)). This makes the 6-defect structure feasible to be used in a 6-beam klystron, when all the beams are modulated synchronously.

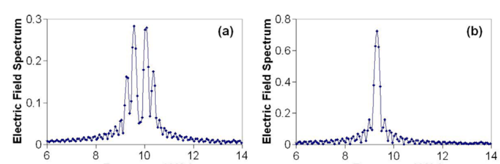

Figure 5: Electric field spectrum of (a). Single-defect excitation. (b). Synchronous 6-defect excitation.

An efficient coupling for the 6-defect structure is via a central stub, as shown in Figure 6 (a). The central stub sees the 6 defects symmetrically and hence only couples to the monopole modes (Figure 6 (b)). This coupling scheme can be applied for both the input and output cavities in a multi-beam klystron of this approach.

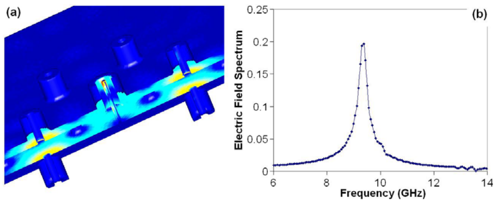

Figure 6: (a). Central stub coupling. (b). Spectrum of stub-coupled field.

A 7-DEFECT KLYSTRON-ACCELERATOR INTEGRATED CAVITY

By replacing the central stub with another beam tube in the 6-defect PC structure, this gives a 7-defect structure (Figure 7 (a)). In this structure, EM fields can be excited in the 6 side defects by velocity-modulated electron beams and couple into the central defect, where the fields highly accumulate and can be used to accelerate particles passing through. This approach utilises a coupled-mode scheme to both create the fields and accelerate particles, hence to achieve a compact design. We have designed a 7-defect structure of r/a=1.5mm/11.5mm and lattice depth 6mm, along with beam tubes of diameter 6mm. 3D Eigenmode simulation using the FEM code COMSOL [12] shows that besides the HOMs shown in Figure 4, there are two modes seen by all the central and side defects, appear as in-phase and anti-phase (Figure 7 (b) & (c)).

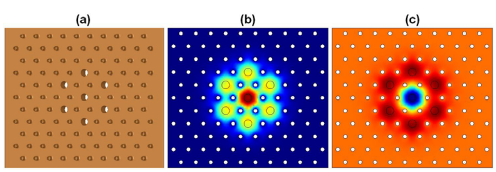

Figure 7: (a). 7-defect structure. (b). In-phase mode at 9.20GHz. (c). Anti-phase mode at 10.37GHz.

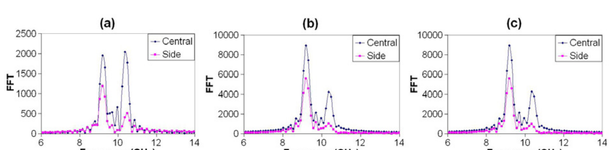

Figure 8: Spectrum of fields at central and side defects for: (a). 1 bunch. (b). 5 bunches. (c). 5 bunches with 1% disorder.

We have verified with VORPAL, that both the in-phase and anti-phase modes can be excited if one bunch is sent into each side defect at the same time (Figure 8 (a)). However, since the frequency difference between the two modes is large (¿1GHz), a beam modulated to the in-phase mode will significantly suppress the anti-phase mode. It is seen from VORPAL simulation that this effect starts taking place significantly for just the first 5 bunches, as shown in Figure 8 (b). We have also estimated the effects from beam instabilities, by introducing 1% disorder randomly to each of the bunch. The field spectrum in Figure 8 (c), compared with Figure 8 (b), shows this level of instability has negligible effect to the field excitation.

In our research, each side defect is loaded with a 300kV 2A electron beam of spot size 4mm, which transits the side defect with beam coupling coefficient M=0.829 and R/Q of 10.031. The structure operates as continuous mode if each beam is moderately modulated to give 0.5A RF current, while 6 beams produce 3A RF current in total (I_1). The maximum gap voltage can be induced at side defect is then

$$V_s = MI_1R_{sh} = 95.4kV \tag{2}$$

This relates to the maximum acceleration voltage 158kV at central defect, which gives a peak acceleration field of 22MV/m.

CONCLUSION

We have experimentally verified the feasibility of using PCs in applications to RF sources from copper PC structures, fabricated to a two-cavity klystron approach. Measurements show only a single mode can be confined at the PC defect, with field strength well agrees with numerical prediction. Multi-defect PCs have been numerically verified to be suitable for building multi-beam klystrons, as well as integrated klystron-accelerator system. We have given a numerical estimation for generating a peak acceleration field of 22MV/m.

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