2D AND 1D SURFACE PHOTONIC BAND GAP STRUCTURES FOR ACCELERATOR APPLICATIONS

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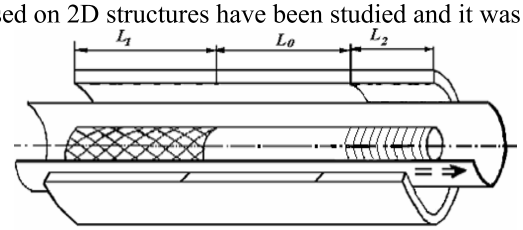
Abstract

First measurements of microwave radiation from a co-axial Free-Electron Maser (FEM), based on a two-mirror cavity, formed by 2D and 1D Surface Photonic Band Gap (SPBG) structures (input and output mirrors) with an intermediate coaxial waveguide are presented. The input mirror provides two-dimensional distributed feedback and ensures mode selection over the wave azimuthal index. The use of a 1D Bragg structure as an output mirror reduces the cavity Q-factor, improves the RF field profiles inside the cavity and increases the output power compared to FEMs based solely on 2D SPBG structures. The FEM has been driven by an oversized, high-current (1.4kA), thin annular electron beam of 200ns pulse duration. An output power of ~60MW corresponding to an efficiency of ~10% was measured. The directional mode pattern of the microwave radiation launched from the output horn was also measured. Using cut-off filters the location of the operating frequency was found to lie between 35 GHz and 39 GHz. The generation of high power microwave pulses in the Ka-band can be adapted to test the breakdown strength of advanced accelerator structures such as CLIC. The possibility to "condition" and to compress the pulse using active 1D SPBG structures is presented. The results of preliminary experiments show that the band gap location can be manipulated by adjustment of the phase between the periodic perturbations of an active 1D SPBG mirror.

NUMERICAL SIMULATIONS

Co-axial Free Electron Masers with two-mirror cavities based on 2D and 1D SPBG structures (fig.1) have been theoretically investigated. In previous work [1-3] FEMs based on 2D structures have been studied and it was



2D Bragg structure as an input mirror *1D Bragg structure as an output mirror*

Figure 1: The schematic diagram of the FEM based on a combined two-mirror cavity.

demonstrated that the use of a two-mirror cavity based on 2D structures as input and output mirrors may result in high RF field ohmic losses and relatively low efficiency. A solution that has been suggested is to use a cavity defined by 2D input and 1D output SPBG mirror [4]. To maximise the FEM gain the 2D time dependent PiC code KARAT was used to simulate FEM operation in the Self Amplified Spontaneous Emission (SASE) regime.

EXPERIMENTAL STUDIES

To drive the FEM a high current accelerator (HCA) based on a magnetically insulated plasma fare carbon cathode was used. A driving electron beam voltage (V_{hsa}) of 440 kV with pulse duration of ~200ns was applied to the HCA and a thin (0.2cm) annular electron beam of current ~1.4kA and mean diameter of 7.0 cm was generated (fig.2). The accelerating voltage and electron

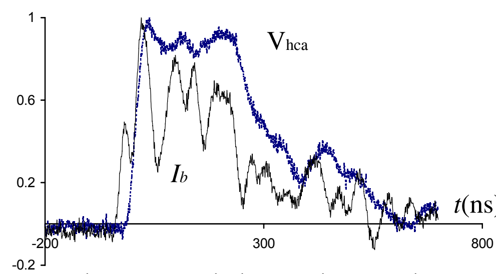


Figure 2: The measured electron beam voltage V_{hca} and current I_b plotted in normalised units

beam current were measured using a voltage divider and Rogowski coil respectively. The electron beam was guided through a co-axial transmission line (~2m long) with inner and outer conductor diameters of 6 and 8 cm respectively. An azimuthally symmetric undulator of period 4 cm was located inside a uniform guide magnetic field, with the undulator field slowly up-tapered over the initial 6 periods. A solenoid of length 2.55m and diameter 30cm surrounding the co-axial electron gun, undulator and co-axial transmission line interaction region was used to guide the electron beam. The amplitude of the undulator magnetic field could be varied up to 0.06 T while the amplitude of the guide magnetic field could be changed up to 1T. The two-mirror cavity of length 81 cm (input 2D SPBG mirror 10.4 cm, output 1D SPBG mirror 10 cm separated by a 60.6 cm uniform co-axial section).

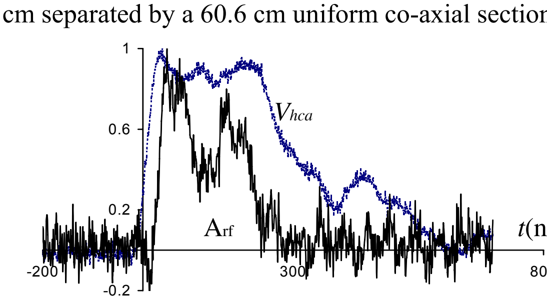


Figure 3: The measured electron beam voltage V_{hca} and microwave signal A_{rf} plotted in normalised units

was located inside the transmission line along the uniform part of the undulator.

To measure the output radiation from the FEM (fig.3) two Ka-band (26.5 to 40GHZ) receiving horns with 60dB of attenuation in conjunction with HP8474E (0.01-50GHz) detectors were located at a distance of 1.5m from the output window. The first horn was "fixed" at the same position during all the experiments to provide a reference signal. The position of the second horn was free to move and was used to study the output radiation characteristics. The output radiation from a conical co-axial horn of inner and outer diameter 6cm and 19cm respectively was measured (fig.4).

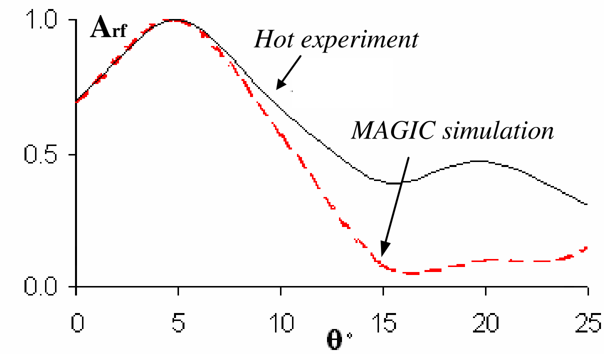


Figure 4: Mode pattern from the output horn measured in experiments (solid line) and simulations (dashed line).

The output power of the FEM was measured by integrating the power densities over space. The total power was calculated to be 60 (±10) MW. The cut-off filters have been used to estimate the location of the operating frequency. It was found that the FEM operating frequency lies in the frequency band from 35 to 39 GHz (fig.5), which is in good agreement with theoretically predicted frequency of 37.3 GHz. In fig.5 the RF pulse power at the detector versus time is presented when 35 GHz and 39 GHz high-pass cut off filters were used. A detailed study of the frequency spectrum of the output radiation using the technique developed in the previous experiments [3] is currently in progress.

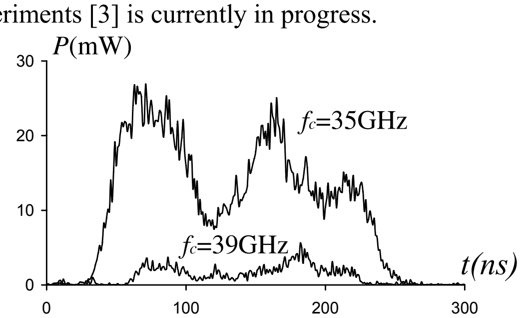


Figure 5: The RF pulse traces when the cut off filters are used

SPBG MIRROR BASED PULSE COMPRESSOR

The concept of microwave pulse compression can be traced back to the late 1960's [5] with the aim of generating high-power pulses, while negating as much as possible the issues arising from an increase in electromagnetic (EM) stresses on circuit components. Pulse compression techniques achieve this by taking lower-power long-duration pulses and compressing them temporally, forcing a higher peak power due to conservation of energy. Various active and passive techniques exist for both frequency swept [6-8] and single frequency pulse compression [9-15] in the microwave regime. The compression technique discussed here works on a novel variation of the switched energy storage (SES) principle [9-10], which utilises a resonance condition to induce pulse compression. The generic SES system is shown in Figure 6.

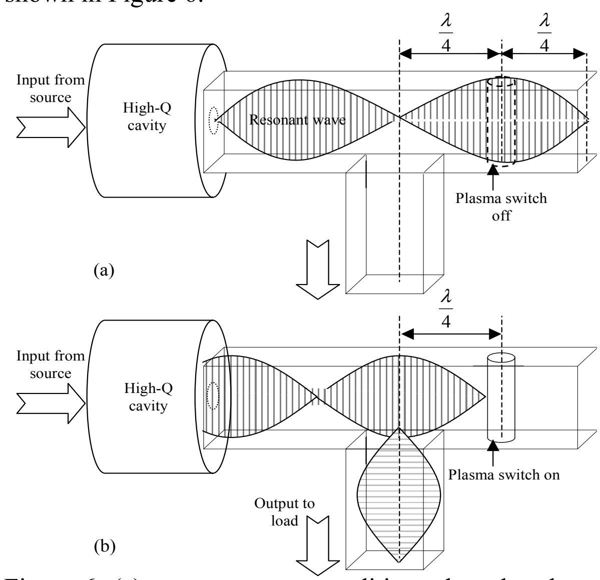


Figure 6: (a) resonant wave condition when the plasma switch is inactive (b) same arrangement with the plasma switch activated.

Essentially SES works by building up a store of energy in a resonant High-Q cavity, with an output coupler positioned at a field minimum (fig.6(a)). A plasma switch positioned at a distance of λ/4 from the coupler allows the effective length of the cavity to be altered, changing the resonance condition and allowing the stored energy to be coupled out to some load (fig.6(b)).

The SPBG based compressor presented here is under development for use in the next generation of particle accelerators and is shown in schematic form in Figure 7. The compressor is created in the same way as the FEM cavity (indicated by the dashed line in fig.7), with a 2D Bragg mirror providing a highly frequency and mode selective mirror at one side and a 1D Bragg mirror at the output, with a series of gas filled envelopes forming the intermediate grooves. The 1D Bragg mirror operates as a low-loss, Q-factor, active modulator. At the initial stage the 1D Bragg structure acts as a high reflection mirror resulting in a high-Q cavity with high-energy storage. At the final stage activation of the switch lowers the cavity Q-factor with the microwave radiation compressed to form higher peak power output pulses. It is important to stress that a 1D structure has been chosen as it allows alternating trapped gas rings to be inserted relatively easily

The inclusion of the gas confined in a dielectric envelope such as glass (forming 1D Bragg grooves) acts

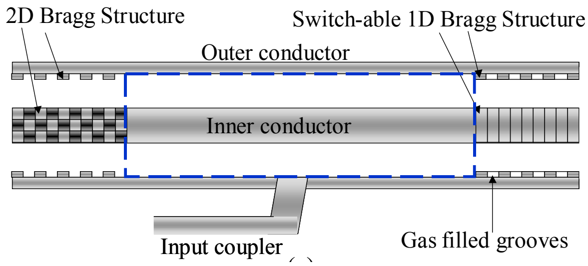


Figure 7: Schematic of the proposed SPBG pulse compressor cavity

as an actively switched plasma at the output of the cavity. By simultaneously passing a current through each of the grooves the trapped gas initiates a plasma which forms a secondary 1D Bragg structure on the outer wall of the cavity that undergoes a phase shift with respect to the original corrugation, as reported in [16]. This will affect the transmission bands of the 1D Bragg mirror as shown in Figure 8, changing the band-gap location and allowing the stored energy to exit.

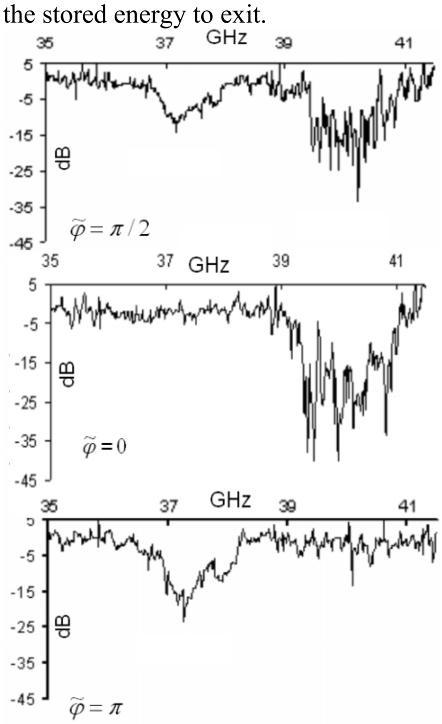


Figure 8: effect of changing the phase between 1D Bragg mirrors on the transmission profile.

The inclusion of such a compressor, at the output of the FEM discussed above, should allow for higher peak power and improved conditioned single frequency output pulses which are useful in accelerator applications, both for the testing components and for providing the RF drive for systems.

CONCLUSION

First measurements of microwave radiation from a co-axial Free-Electron Maser (FEM) based on a combined (2D-1D) two-mirror cavity are presented, along with preliminary work on a pulse compressor cavity utilising a similar topology. The FEM has been driven with an electron beam of 1.4kA and 440kV achieving a maximum output power of ~60MW with an efficiency of ~10%. Using cut-off filters it was shown that the FEM operating frequency was located in the range from 35GHz to 39GHz. Coherent microwave radiation at 60MW with energy storage in a single pulse of up to 10J in the Ka frequency band is useful for accelerator applications. For example this technology can be adapted to produce high power (~100MW) microwave radiation at a frequency of 30GHz required for the testing structures used in advanced accelerators such as CLIC. Future work will involve detailed study of the output radiation spectrum and further optimisation of the cavity configuration to achieve higher efficiency and higher operation power. The development of the compressor will provide a degree of pulse conditioning to the output, providing a more stable RF pulse which could be suitable for accelerator based applications.

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REFERENCES

[1] N. S. Ginzburg et al., J. Appl. Phys., **92**, 2002, p.1619.
[2] A. W. Cross et al., Appl. Phys. Lett, **80**, 2002, p.1517.
[3] I. V. Konoplev et al., Phys. Rev. Lett, **96**, 035002, 2006
[4] N.S Ginzburg et al., Phys. Plasmas, **9**, p. 2798, 2002
[5] R.A Bromley, B.E. Callan, Proc. IEE, **114**, 1967. p.1213
[6] S. M. Vlasov et al., Tech. Phys., **33**, p.209, 1998
[7] S. V. Samsonov, et al. Phys, Rev. Lett., **92**, 118301, 2000
[8] G. Burt et al., IEEE Trans. Plasma Sci., **33**, p.661 2005
[9] R. Alvarez et al. IEEE Trans. Mag. MAG-17 (1), p.935, 1981.
[10] D. Birx et al., Appl. Phys. Lett., **32**, p. 68, 1978
[11] Z. D. Farkas et al., SLAC pub.1453, 1974
[12] Z. D. Farkas et al., SLAC pub.1561, 1975
[13] P. B. Wilson et al., SLAC pub.5330, 1990
[14] S. G. Tantawi et al., SLAC pub.6775, 1995
[15] Z. D. Farkas et al., SLAC pub.3694, 1985
[16] I. V. Konoplev et al., Appl. Phys. Lett., **87**, 121104, 2005