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Compact millimetre wave and terahertz radiation sources driven by pseudospark-generated electron beam

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Abstract

A pseudospark (PS) plasma sourced electron beam was both computationally and experimentally studied for generation of millimetre wave and terahertz radiation. The beam-wave interaction region is a sinusoidal rippled-wall slow wave structure of a backward wave oscillator (BWO) in G-band. An electron beam of ~1 mm diameter carrying a current of up to 10 A with a sweeping voltage of 42 to 25 kV and pulse duration of 25 ns propagated through the interaction region in a plasma environment without the need for a guiding magnetic field, which resulted in broadband millimetre radiation generation over a frequency range of 186-202 GHz with a maximum power of 20 W.

1 Introduction

Radiation in the frequency range from 100 GHz to 1 THz in the quasi optical regime with properties of both wave and light have many exciting applications such as in electron spin resonance spectroscopy, remote imaging, and fast speed mobile communications. Nevertheless their generation has been a recognized technological gap called the terahertz gap, where conventional optical and electronic technologies are struggling to provide good frequency bandwidth at even rather moderate power levels. Addressing this power-bandwidth deficit in the hundreds of GHz range a table-top Backward Wave Oscillator (BWO) based on a pseudospark (PS) electron beam was studied for the first time. To achieve higher BWO output power levels in the THz range, a higher current density electron beam is required, preferably of the order of $10^6 Am^{-2}$. In satisfying the beam requirements for THz devices, the pseudospark-sourced electron beam has appeared to be very attractive, with the highest combined beam current density ($>10^8 Am^{-2}$) and brightness (up to $10^{12} Am^{-2} rad^{-2}$) [1,2].

A PS electron beam is generated during a PS discharge, which is an axially symmetric, transient, low pressure (typically 50-500 mTorr) gas discharge in a hollow cathode / planar anode configuration which operates on the left-hand side (with respect to the minimum) of the hollow-cathode analogy to the Paschen curve[3,4]. During a PS discharge, low temperature plasma is formed that acts as a copious source of electrons facilitating electron extraction to form electron beam of diameters in the range from millimetre to microns. The propagation property of this PS sourced beam is further investigated experimentally and in simulation, which proved the beam's propagation without external guiding magnetic field and its potential applications in the generation of millimetre wave and sub terahertz radiation [5-8].

A G-band BWO with a PS-sourced pencil electron beam was investigated. In this article the simulation results which agree well with experimental measurements are reported.

2 Experiments and Simulations

The experimental configuration is shown in Fig. 1. The discharge chamber in the PS discharge system consisted of a planar anode and a planar cathode with a cylindrical hollow cavity, between which were placed three intermediate electrodes of 3 mm thickness and four Perspex insulation discs of 4 mm thickness. The anode and cathode and electrodes were made of stainless steel and have an on-axis hole of 3 mm diameter. In order to extract micro-sized beams from the PS discharge chamber, stainless steel collimating structures were attached to the anode. The hollow cathode cavity, also made of stainless steel, has a length of 50 mm and a diameter of 50 mm. An external energy storage capacitor Cext of 600 pF across the cathode and anode was used to control the discharge duration and hence the electron beam duration. A rotary pump evacuated the experimental system from the anode end through a vacuum valve. The working gas (in this case, air) entered the chamber through a very fine adjustable needle valve at the anode side and its pressure was measured by a capacitance manometer-type vacuum gauge. The hollow cathode was connected through a charging resistor of 10 MΩ to a negative high voltage source while the anode was grounded. A capacitive voltage probe with a sub-nanosecond response time was connected to the cathode to measure the applied and discharge voltage. Measurements of the beam current were realized using a Rogowski current probe attached to the anode and followed by the drift tube.

When a high voltage is applied to the hollow cathode, the electric field across the anode-cathode gap penetrates a short distance into the hollow cathode region due to the small cathode aperture. A PS discharge will occur if the pressure in the system is suitably low (typically 50-500 mTorr and approximately 110 mTorr in this experiment) so that the discharge is at the left-hand side (with respect to the minimum) of the Paschen curve. In such a PS discharge condition, the gas breakdown will occur along the longest possible path, allowing a virtual anode to form, extending from the anode into the hollow cathode region. As the virtual anode reaches the cathode surface field-enhanced emission begins to occur. Electrons begin emitting from the cathode surface at an increased rate, augmented by secondary emission and are accelerated toward the aperture by the electric field. Consequentially this rapid increase in electron emission results in a rapid increase in the beam current. As the beam propagates through the anode its front edge ionizes the background gas, forming a plasma channel, while the following beam electrons expel part of the plasma electrons so that an ion-channel is formed, confining the beam and eliminating the need for any external magnetic guide field. A high current density, high brightness electron beam with a sweeping voltage can therefore be generated and propagated by ion channel focusing.

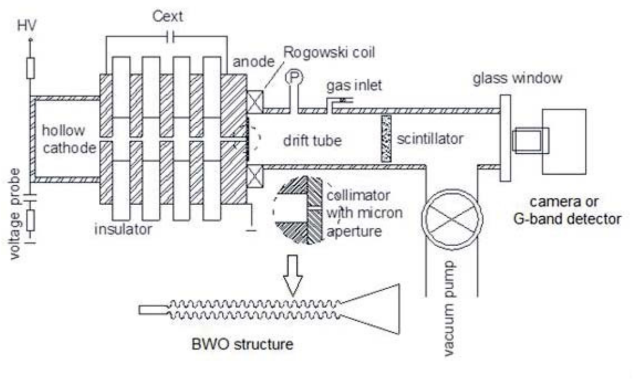

Fig. 1 Experimental setup of the micro electron beam generation from a DC-powered 4-gap PS discharge and BWO experiment.

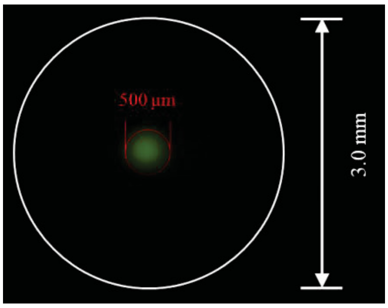

Fig. 2 Image of electron beam imprint on phosphor scintillator for a single pulse

Images of the generated beams were obtained by inserting a scintillator disk made from 1 μm thickness copper foil coated with scintillation powder (Plano P47, Agar Scientific Ltd., UK) 60 mm downstream of the anode with pictures taken with a high-speed digital camera located at the end of the drift tube. A ~500 μm beam image was recorded and is shown in Fig. 2 when a collimator of 500 μm aperture size was used. For the BWO interaction in the sub-terahertz range, a 1 mm diameter electron beam was used.

For the PS-based BWO experiment, a plasma background forms in the SWS due to the ionization of the neutral background gas, which will affect the dispersion characteristic of the waveguide with, or without, a magnetic field. After consideration of the beam plasma frequency and the Doppler shift term of the beam dispersion, the beam-wave interaction in the BWO SWS is simulated by the 2D particle-in-cell (PIC) simulation code MAGIC. The dimensions of the SWS used in the simulations are the same as the measured dimensions of the SWS in the experiments, namely the mean radius of 610 μm, the corrugation depth of 130 μm, and the period of 470 μm with a beam wave interaction of 25 periods. It was designed to be able to interact over a large beam voltage range to maximize the output power. Fig. 3 shows the predicted output power and frequency spectrum. The simulation also shows that stable propagation of the electron beam, which happens during the PS discharge process, requires a background plasma density of approximately 6.5×10^{19} m^{-3}. The electron beam will not propagate stably in a higher plasma density and becomes defocused in a lower value.

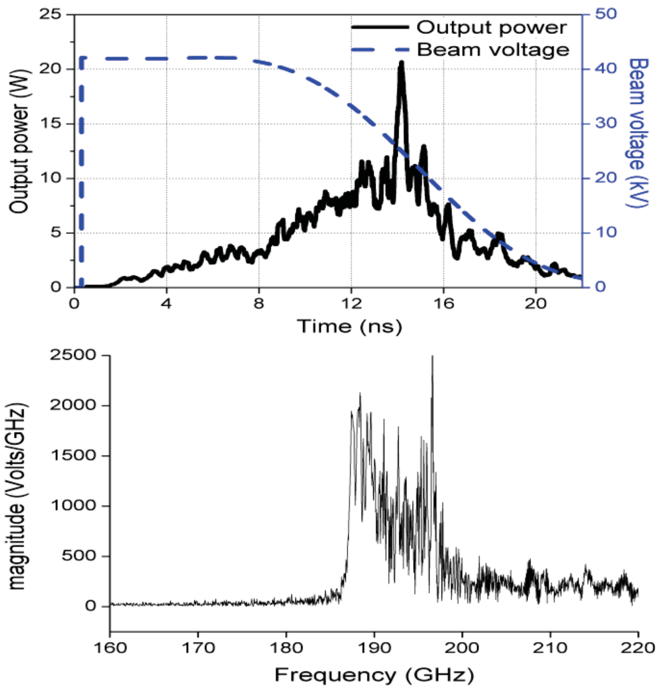

Fig. 3 BWO output power (top) and frequency spectrum (bottom) as predicted using 2D PIC code MAGIC

The BWO structure, together with the conical radiation launching horn was manufactured by high speed grinding of an aluminium former and the subsequent electro-deposition of a 5 mm thick layer of copper on the aluminium former, which was later dissolved away in an alkali solution.

The PS discharge was initiated with a collimator of aperture size 1 mm and the rippled-wall BWO SWS was integrated into the anode aperture. Radiation pulses were measured using a semiconductor rectifying diode (ELVA-1 Microwave Ltd., ZBD-05, 140-220 GHz) situated 30 mm from the BWO launching horn. A heterodyne frequency diagnostic was used to measure the frequency of the output radiation of the BWO. A sub-harmonic mixer (Millitech MSH-05-2NI00) and a local oscillator signal produced from a 95 GHz Gunn diode

(Millitech GDM-10-1013IR) were used and the resultant intermediate frequency (IF) signal was recorded using a 20 GHz, deep memory digitizing oscilloscope (Agilent DSX-X 92004 A).

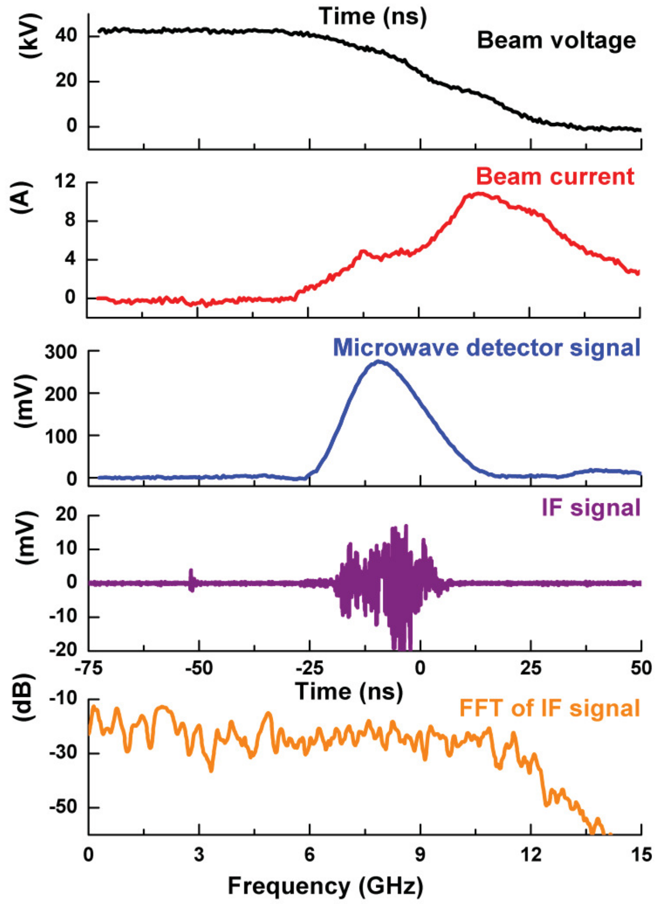

Fig. 4 Time-correlated electron beam voltage, current pulse, the millimetre wave pulse from the 200 GHz BWO, the intermediate frequency (IF) output from a harmonic mixer recorded on a deep memory (20 GHz) single shot digital storage oscilloscope and FFT result of the intermediate frequency output.

Fig. 4 shows the repeatable time-correlated electron beam voltage, the discharge current and the millimetre wave pulse. The electron beam current has a step of about 5 A at the hollow cathode discharge phase and then a peak current of about 10 A follows in the conductive phase. The microwave radiation was mainly generated near this first 5 A step, because the correlated beam voltage has stronger coupling with the BWO structure. In the conductive phase, the beam voltage is too low to have efficient beam-wave interaction. The output power was ascertained using the general antenna theorem with the total power from a launching antenna, calculated by integrating its radiated power density over space. The integration was completed by numerically integrating the normalized mode profile of the launching horn and multiplying by the measured maximum power density. In doing so, the total power of the BWO in this frequency range was found to be 20 W.

3 Conclusion

The generation of smaller electron beams from the PS source show the potential for the generation of signals moving towards the mid-THz range while still producing powers which rival, if not exceed, those of vacuum electronic sources operating at similar frequencies. As such, while these experimental results are a major advance and have matched well with the output predicted by simulations, they may be seen as an indicator of even greater performance in the future, making such PS-plasma assisted BWO devices of great interest in a variety of application areas.

Acknowledgements

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References

[1] A. W. Cross, H. Yin, W. He, K. Ronald, A. D. R. Phelps, and L. C. Pitchford, “Generation and application of pseudospark-sourced electron beam", *J. Phys. D: Appl. Phys.* **40**, pp. 1953-1956, (2007).

[2] H. Yin, A.W. Cross, A. D. R. Phelps, et al., “Propagation and post-acceleration of a pseudospark-sourced electron beam,” *J. Appl. Phys.*, vol. 91, no.8, pp. 5419-5422, (2002).

[3] K. Frank and J. Christiansen, “The Fundamentals of the Pseudospark and Its Applications”, *IEEE Trans. Plasma Sci.* **17**, pp. 748-753, (1989).

[4] H. Yin, A. W. Cross, W. He, A. D. R. Phelps, K. Ronald, D. Bowes, and C. W. Robertson, “Millimeter wave generation from a pseudospark-sourced electron beam", *Phys. Plasmas* **16**, pp. 063105-1–063105-6, (2009)

[5] Y. Yin, W. He, L. Zhang, H. Yin, and A. W. Cross, “Preliminary design and optimization of a G-band extended interaction oscillator based on a PS-sourced electron beam”, *Phys. Plasmas*, **22**, pp. 073102-1–073102-6, (2015).

[6] W. He, L. Zhang, D. Bowes, H. Yin, K. Ronald, A. D. R. Phelps, and A. W. Cross, "Generation of broadband terahertz radiation using a backward wave oscillator and pseudospark-sourced electron beam", *Appl. Phys. Lett*., **107**, pp. 133501-1–133501-4, (2015).

[7] Y. Yin, W. He, L. Zhang, H. Yin, C. W. Robertson and A. W. Cross, "Simulation and experiments of a W-band Extended Interaction Oscillator based on a pseudospark-sourced electron beam", *IEEE Trans. Electron Devices,* **63**, pp. 512-516, (2016).

[8] H. Yin, G. R. M. Robb, W. He, et al. “Pseudospark-based electron beam and cherenkov maser experiments,” *Phys. Plasmas.*, **7**, no.12, pp. 5195-5205, (2000).