High-order photonic bandgap reflex klystron using carbon nanotube multi-beam cathode

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The oscillation of a high-order mode TM_{330} is observed in a photonic bandgap multi-beam reflex klystron using nine electron beams generated from a carbon nanotube cathode. One side of a conventional metal cavity was replaced with a dielectric photonic crystal lattice to form a hybrid photonic-bandgap resonator, which uses lattice bandgap effects, resulting in a more uniform field of a higher-order mode, as well as the exclusion of some conventional-cavity-type modes, thereby reducing mode competition. The high-order and multi-beam concepts would be applicable to a terahertz radiation source when the device is micromachined.

Introduction: With the advent of terahertz (THz) sources, new vistas of applications, such as the imaging of biological tissues, spectroscopic identification of complex molecules, and broadband communications, have been opened up [1–3]. The present-day requirement is to develop compact and inexpensive THz devices with reasonable power levels for practical applications. There has been significant progress in the development of quantum optical and solid-state devices such as quantum cascade lasers and resonant tunnelling diodes that operate at THz frequencies. An alternative to achieving reasonable power levels in the THz regime is to use micro-fabricated vacuum microelectronic devices that accrue the advantages of both microelectronics technology and vacuum electron devices over their solid-state counterparts.

Circuit design: In this Letter, a feasibility study is conducted on the development of a reflex klystron, in a higher-order mode, TM_{330}, for the THz regime. The proof-of-concept experiment uses the scaled down frequency of the X-band (10.5 GHz), a carbon nanotube (CNT) paste cathode and a hybrid photonic bandgap (PBG) cavity in the multi-beam configuration, and nine beams providing a high beam current as well as compactness owing to the diode-type emission test, a 500 μm-thick glass spacer was used to provide separation between the cavity and the anode, as shown in Fig. 2a. A pulsed voltage of 5 μs duration and at a repetition rate of 5 Hz was applied to the anode. The potential of the anode with respect to the cathode was increased up to 5 kV, in steps of 0.5 kV, corresponding to an electric field of 10 V/μm, where it was kept for an hour, as shown in Fig. 2b, to observe any degradation in the emission of the cathode [8] in terms of diode current density. Subsequently, the measurement was repeated for higher fields such as 11, 12, 13, and 14 V/μm. The aging process was observed to stabilise after minutes, and the emission current at various electric fields decreased to half of its initial value.

The CNT cathode, which generates a 3 × 3 multi-beam, was positioned on the hybrid PBG resonator as shown in Fig. 3 using a circuit design:

- **Diode emission test setup**: Nine electron beams were prepared using CNT field emitters. Although there is still a need to improve the lifetime of CNT emitters before they can be employed in a practical vacuum electronic device, in view of the relatively large cathode sizes required for our X-band experiment and the easy manageability of the screen-printing process [7], we preferred to use the latter in the fabrication of the cathode. The multi-walled CNT paste was printed on a copper plate covered with a wire screen. It was designed to fit into the TM_{330} modes (with the distance between the cathodes kept at 20 mm, and the radius of the cathode at 3 mm) of the hybrid PBG cavity. The emission uniformity was checked using a phosphor screen, see Fig. 2a, and then the metal anode was used to study the I-V characteristics of the nine CNT cathodes. Their dependence on time was also observed as shown in Fig. 2b. To perform the diode-type emission test, a 500 μm-thick glass spacer was used to provide separation between the cathode and the anode, as shown in Fig. 2a.

**Fig. 1** Simulated electric field contours for TM_{330} mode at location of electron beams of devices (left) and momentum of nine electron beams modulated by TM_{330} mode (right).

Inset: FFT of excited electromagnetic wave

The gap between the grids of the cavity and the distance of the repeller from the cavity were 0.7 and 6 mm, respectively. It was designed with due consideration to the low-voltage operation of the device. A particle-in-cell (PIC) simulation (MAGIC 3D) [6] was carried out to generate the contour plot of the TM_{330} mode electric field pattern of the hybrid PBG cavity of the reflex klystron (with the direction of the field shown normal to the page) (Fig. 1). In the simulation, nine electron beams were considered at the centres of the TM_{330}-like mode, with each beam carrying a current of 200 mA and accelerated at 1 kV potential. The repeller voltage of the device was kept at 3.7 kV, corresponding to the optimum phase angle of 15/4 cycles (n = 4) at the operating frequency (10.5 GHz) of the device. Further, the results of the fast Fourier transform (FFT), shown in the inset of Fig. 1, confirm the excitation of only the desired TM_{330} mode at the operating frequency; Fig. 1 also gives the velocity modulation diagram of the electrons in each beam in terms of the axial momentum normalised with respect to the initial axial momentum. Only two curves are shown in the Figure, instead of nine (corresponding to nine beams). There are nine uniform electric field distributions with a phase difference of π between the two neighbouring beams (Fig. 1b). The simulation picture shown in Fig. 1 demonstrates that the TM_{330}-like mode is excited dominantly in the hybrid PBG resonator, without mode competition and without any distortion caused by the presence of the output coupling system.

**Fig. 2** CNT cathode emission test setup

- a Diode test setup comprising CNT cathode and phosphor-screen anode, separated from cathode by 0.5 mm-thick glass spacer and its emission uniformity.
- b Emission behaviour of CNT cathode under tests in terms of I-V characteristics and its degradation characteristics with time in experimental diode setup

**Fig. 3** Experimental setup for measuring grid transparency (nine screen-printed CNT cathodes on copper plate and devised PBG circuit are displayed).
200 μm-thick glass spacer for achieving an operating voltage of approximately 1–2 kV. Before applying the repeller bias voltage, both the emission current at the cathode and the transmitted current through the grid were measured.

Grids of 100 μm were equally spaced at a distance of 300 μm both vertically and horizontally. About half of the total emission current from the nine cathodes passed through the grids to reach the repeller. The rest of the current was intercepted by the grids, as shown in Fig. 4 (left). The experiment on the excitation of high-order mode, TM_{330}, was carried out at a beam voltage of 2.5 kV with a corresponding beam current of 66 mA for each beamlet. That is because the PIC simulation showed that at the operating voltage more than 40 mA of current for each beamlet would be required to start oscillation at the electronic mode numbers of n = 5 and n = 6. Also, the repetition frequency of the 5 μs-duration pulsed voltage was reduced to 1 Hz to delay the CNT degradation.

Fig. 4 Total emission current at nine cathodes and transmitted current through the grid were measured (left). Simulated and measured output power. Excited electron mode numbers correspond to n = 5 and n = 6 of designed reflex klystron (right)

An RF power measurement was then carried out by varying the repeller voltage from 3 to 6 kV. Notwithstanding a decline in emission current at the high field operation of the CNT cathode during the experiment, high-mode (TM_{330}) excitation was observed, as illustrated in Fig. 4 (right). To estimate the excited electronic mode number [5], we ran the PIC simulation (MAGIC 3D) at the same electron beam condition of the experimental measurements. The simulated oscillation repeller voltages in Fig. 4 (right) indicated that the excited electronic modes were n = 5 and n = 6. This ascertained that the excited mode was TM_{330} for the cavity, in spite of simulation results estimating the power output deviation due to the degradation of CNT emitters.

Conclusion: An X-band photonic bandgap multi-beam reflex klystron has been experimentally realised at the TM_{330}-like mode using CNT cathodes. It has potential applications as a terahertz radiation source.

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