Photonic-Band-Gap Resonator Gyrotron

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(Received 15 February 2001)

We report the design and experimental demonstration of a gyrotron oscillator using a photonic-band-gap (PBG) structure to eliminate mode competition in a highly overmoded resonator. The PBG cavity supports a TE_{041}-like mode at 140 GHz and is designed to have no competing modes over a minimum frequency range $\delta\omega/\omega$ of 30% about the design mode. Experimental operation of a PBG gyrotron at 68 kV and 5 A produced 25 kW of peak power in the design mode. No other modes were observed over the full predicted operating range about the design mode. PBG cavities show great promise for applications in vacuum electron devices in the millimeter- and submillimeter-wave bands.

DOI: 10.1103/PhysRevLett.86.5628 PACS numbers: 84.40.Ik, 07.57.Hm, 42.70.Qs, 84.40.Fe

Vacuum electron devices are important sources of high power microwave radiation for use in industrial heating, plasma heating, radar, communications, accelerators, spectroscopy, and many other applications [1]. Extension of the operating frequency of these sources to higher frequency is of great interest and would open up many new applications. One obstacle to the extension of the operating frequency is that high power, high frequency devices must operate in overmoded structures for several reasons. As the frequency increases to the millimeter-wave range, fundamental mode resonators have sub-mm dimensions so that accurate fabrication is difficult and expensive, the heat load per unit area on resonator walls becomes excessive. It is also very difficult to pass an electron beam through such small structures without beam interception. Although overmoded resonators alleviate these problems, their pitfall is mode competition — a limiting factor in the design and operation of millimeter-wave gyrotrons.

We report on a promising approach to overcome the problem of mode competition in overmoded structures, namely, the use of photonic-band-gap (PBG) cavities. A photonic-band-gap structure, which is a periodic array of varying dielectric or metallic structures, was first described by Yablonovitch *et al.* [2]. In recent years, numerous advances have improved our understanding of the theory of PBG structures [3]. This has led to new applications in passive devices for guiding and confinement of electromagnetic radiation. Their use in both microwave and optical devices has primarily been limited to passive devices such as waveguides and filters [4,5], though some applications in active devices have been reported [6]. The results of the investigation of the potential of PBG structures for accelerator cavities are also very promising [7,8].

Gyrotron oscillators and amplifiers have made great progress in recent years [1]. Impressive results for gyrotron amplifiers were obtained in the TE_{11} fundamental mode of the circular waveguide [9], where mode competition and conversion are absent. These excellent results cannot be extended to higher frequencies ($\sim$100 GHz) because the waveguide structure would be too small. Advanced research on a high power W-band gyroklystron amplifier was successfully carried out in a slightly overmoded structure with the TE_{01} mode — the third TE mode of a cylindrical waveguide [10]. Our results differ from those results in that they are in a much more highly overmoded structure and demonstrate operation in a very high order mode (TE_{04}-like mode — the 30th TE mode supported by a cylindrical waveguide) without mode competition. In gyrotron oscillators, successful operation can be obtained in overmoded cavities if careful techniques of cavity design are used together with placement of the electron beam at the optimum radius for the desired mode. However, at very high frequency, mode competition is still a major issue for gyrotron oscillators [11,12]. For devices in which mode competition is a limiting factor, the PBG cavity will be advantageous, especially at moderate power levels.

In our research, we have chosen to demonstrate the PBG gyrotron as a 140 GHz oscillator because of the availability of equipment in our laboratory. The present experiment is modeled on a previous device we have studied, a 140 GHz conventional cavity gyrotron oscillator operating in the TE_{031} mode [13]. The reduced mode competition observed in these experiments and described below represents a clear and dramatic improvement over earlier results with a conventional cavity. To our knowledge, the present results are the first use of a PBG cavity in an active high power microwave device.

The electromagnetic radiation in a gyrotron is produced by the interaction of a mildly relativistic gyrating electron beam and TE wave close to cutoff in a cavity resonator. The oscillation frequency ω, of a TE_{mnq} mode of a cylindrical cavity of length L and radius r_0, is given by

$$\omega^2/c^2 = k^2 = k_\perp^2 + k_z^2, \tag{1}$$

where $k_\perp$ ($= \nu_{mn}/r_0$) and k_z ($= q\pi/L \ll k_\perp$) are the transverse and longitudinal propagation constants of the TE_{mnq} wave, c is the speed of light, ν_{mn} is the nth root of $J_m'(x) = 0$, and q is an integer. The resonance condition for the excitation of the cyclotron resonance maser instability is satisfied when ω and k_z in (1) satisfy the beam

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mode dispersion relation

$$\omega - k_z \beta_{z0} c \gtrsim s \omega_{c_0} / \gamma \,, \tag{2}$$

where ω_{c0} ($= eB_0/m_e$) is the cyclotron frequency, $\gamma = (1 - \beta_{z0}^2 - \beta_{\perp 0}^2)^{-1/2}$ is the relativistic mass factor, $\beta_{\perp 0}$ and β_{z0} are, respectively, the transverse and longitudinal velocities of the electrons normalized to the velocity of light, s is the cyclotron harmonic number ($s = 1$ in this experiment), and B_0 is the magnitude of the static axial magnetic field.

The beam parameters, the cavity dimensions, and an optimum detuning can be determined from the procedure outlined in [14–16] to optimize the interaction efficiency. The choice of the operating mode is dictated by the cavity Ohmic heat capacity and the window for stable single-mode excitation at a high interaction efficiency. It is often noticed in gyrotrons that, while optimizing the detuning of the magnetic field to increase the interaction efficiency, the device slips into a different mode if the excitation conditions for the latter mode are satisfied. This mode hopping in a high mode density resonator can prevent the access to the high efficiency operating regime of the design mode, but, with the use of a properly chosen start-up scenario, it can be avoided [11,12].

Traditional gyrotron cavities are cylindrical copper cavities with a downtaper to the cutoff radius at the entrance for mode confinement and an uptaper at the exit for output coupling [17]. In these experiments the cylindrical outer copper wall is replaced with a PBG structure comprised of a triangular lattice of metal rods. These rods are placed parallel to one another and parallel to the axis of the gyrotron and magnetic field system. Two oxygen-free high conductivity copper plates with an array of holes maintain the rods in position and form the end plates of a PBG gyrotron cavity, as shown in Fig. 1. A number of rods are omitted from the center of the array to support a mode. A high order TE-like waveguide mode can now exist in this hole if its resonant frequency lies in the band gap or stop band of the PBG structure. The band gap can be adjusted such that the resonant frequencies of all other neighboring modes lie in the passband of the lattice and hence can leak through the array that acts like a transparent wall at those frequencies. Radiation that passes through the array propagates out and is not reflected back into the lattice, permitting a strong single-mode operation in the design mode. 102 copper rods of 1.59 mm diameter are held in a triangular array with 2.03 mm spacing between the rods (center to center) to form the PBG structure (Fig. 1). Initial lattice dimensions were chosen by using an analytic theory and simulations in SUPERFISH [18]; subsequently, simulations using HFSS (High Frequency Structure Simulator, Ansoft Corp.) helped refine these dimensions. A cross section of the HFSS model of the PBG gyrotron cavity is shown in Fig. 2. In the figure, an empty circle designates the location of the rods since no electric field can exist at that location. The array can hold 121 rods but the 19 innermost rods have been omitted to form the cavity. The frequency of the confined eigenmode shown in the model (Fig. 2) is 139.97 GHz in the TE_{041}-like mode of a conventional cylindrical cavity.

The nominal operating voltage is 68 kV at a current of 5 A, with a beam velocity pitch factor ($\alpha = \beta_{\perp 0}/\beta_{z0}$) equal to 1.2. The pitch factor α can be varied from 1.0 to 2.0 by varying the modulating anode voltage or the magnetic field at the cathode. A moderate velocity pitch factor ($\alpha \sim 1.2$) was chosen to keep the velocity spread in the beam below 6% and to prevent overbunching of the beam.

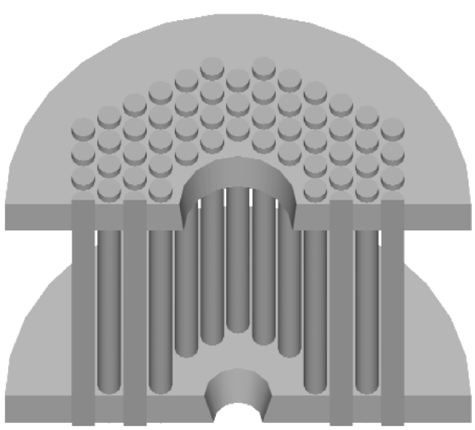

FIG. 1. A section of the computer aided design drawing of the PBG resonator used in the gyrotron experiment. The small aperture on the lower end plate forms the input cutoff section and the bigger hole on the upper end plate is used to extract the radiation from the cavity.

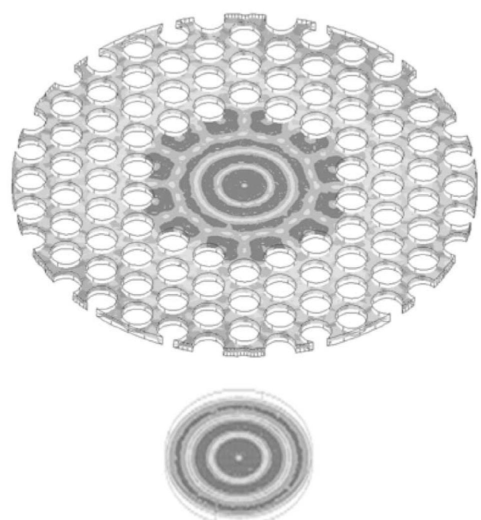

FIG. 2. Comparison of the TE_{041}-like eigenmode of the PBG cavity (top) and the TE_{041} eigenmode in a conventional cylindrical cavity (bottom). The above simulations showing the magnitude of the electric field were performed using HFSS. The darker regions indicate a higher electric field intensity. The PBG structure is 23 mm in diameter while the cylindrical cavity is 9 mm in diameter.

The radius of the hollow electron beam is 1.82 mm which is the correct radius to excite the TE_{04}-like mode at its second radial maximum. The length of the cavity was chosen to be eight wavelengths of the operating frequency (140 GHz) in order to optimize the efficiency.

A hollow annular electron beam from a magnetron injection gun (MIG) was guided through the PBG cavity immersed in a 5.4 T magnetic field provided by a superconducting magnet. A schematic of the experimental setup is shown in Fig. 3. The electron beam traversed the PBG cavity along its axis, passing through the holes in the end plates. The spent electron beam emerging from the cavity after interaction was collected by a steel pipe which also served as a waveguide to transport the electromagnetic radiation from the cavity to the window of the gyrotron.

In order to test the PBG gyrotron oscillator for mode selectivity, the device was operated at 68 kV, 5 A over the magnetic field range of 4.1–5.8 T to permit beam transmission without significant reflection or interception over the whole range. As indicated in Eq. (2), this range in magnetic field tuning corresponds to an equal range of frequency tuning, about 30%. The variation of output power with the magnetic field, the most vital indicator of the mode selectivity of the cavity, is shown in Fig. 4. The mode with an operating frequency of 140.05 GHz is the only strong mode emanating from the cavity. This result is direct confirmation of the mode selectivity of the PBG cavity. A conventional cylindrical cavity, operating in the TE_{041} mode over the same range of magnetic field tuning of 30% as in this experiment, would face strong competition from at least seven other modes. One of those competing modes, the TE_{241} mode, which is nearly degenerate with the TE_{041} mode and severely reduces its operating range and efficiency [19] is absent in the PBG structure. The maximum power recorded in the design mode for the operating voltage and current used for the magnetic field scan is about 16 kW. Operation at a different voltage and current produced up to 25 kW at an efficiency of 7%. The power in the operating mode was measured by a Scientech Calorimeter, Model 36-0401. The surface absorbing layer of the calorimeter is increased to optimize absorption at 140 GHz. The details of the modification to the calorimeter are discussed in [13]. The frequency was measured by a heterodyne receiver system with a harmonic mixer and filters.

At magnetic field values away from the high power operating mode, the gyrotron oscillator has very weak emission in other modes. The presence of these modes was detected using either a WR-8 video diode detector or a heterodyne receiver system. The video diode could detect signals with power as low as 1 W, which is 44 dB down from the main signal. The calibrated diode measurements confirmed that the power in the points shown as 0 kW in Fig. 4 was everywhere less than 100 W, which is at least 22 dB below the main mode and represents an efficiency of less than 0.03%. These weak spurious modes may be generated in the output waveguide structure of the gyrotron. Detailed investigation of the nature of these modes was not conducted in this experiment.

For convenience, in these first experiments, we have used a flat plate with a hole for output coupling. HFSS simulations predict an Ohmic Q factor of about 13 500 and a diffractive Q factor of about 16 000 for this PBG cavity; these Q factors were not measured in cold test. The theoretical Ohmic Q factor is comparable to that of an equivalent cylindrical resonator. The ratio of the estimated diffraction and Ohmic Q factors implies that more than half of the generated power is trapped inside the cavity, leading to a reduced efficiency of the device. In the future, we plan to test PBG cavities with optimized output coupling including transverse coupling to reduce the diffraction Q factor. We have previously studied transverse coupling in a test structure at 17 GHz and obtained excellent results coupling into and out of a PBG structure [20]. For the operating parameters chosen in the experiment and the ratio

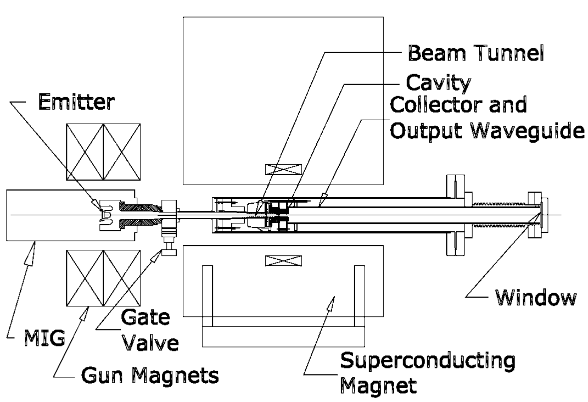

FIG. 3. Setup of the PBG gyrotron experiment. The pumping ports and other diagnostic features are not shown. The total length of the gyrotron tube is about 1.4 m.

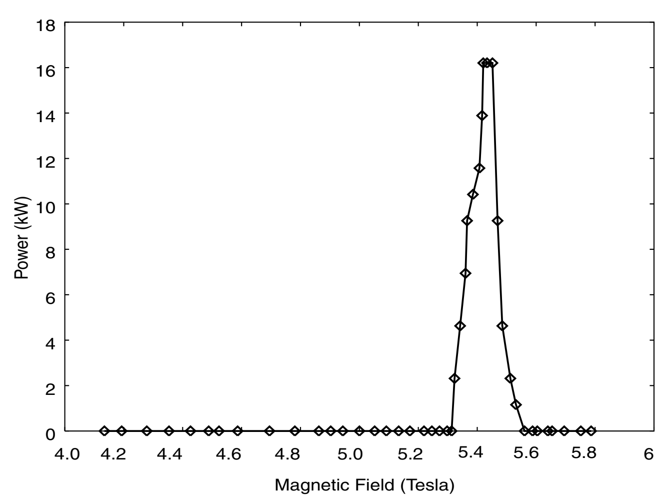

FIG. 4. The variation of output power of the gyrotron with the main magnetic field. The radiation frequency is 140.05 GHz in a TE_{041}-like mode.

of the diffractive Q to the Ohmic Q, the experimentally observed efficiency agrees well with the predictions from a nonlinear theory [14–16].

The PBG cavity appears to be very useful in gyrotron oscillator applications at moderate average power levels. At high average power, however, the rods of the PBG structure may not be able to dissipate Ohmic losses as effectively as the smooth walls of conventional cylindrical cavities. This can be mitigated by using thicker rods and by cooling the rods with water flowing through channels in the center of each rod. The PBG structures would be able to handle high peak power levels, and would be particularly well suited to high peak power, moderate average power level amplifiers. They are also very attractive for use as the buncher cavities in amplifiers at any power level. At very high frequencies, where moderate power levels are of interest, the PBG structures also appear to be very attractive. A potential application would be a high power (>10 kW) conventional millimeter-wave klystron or coupled-cavity traveling wave tube operating in a higher order mode with a PBG cavity.

This work was supported by the Department of Defense, under the MURI Innovative Microwave Vacuum Electronics Program, and the Department of Energy, Office of Fusion Energy Sciences. The authors thank William Mulligan for his help in running the experiments and Chiping Chen for his comments on PBG cavity designs.

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