Frequency Tunable Gyrotron Using Backward-wave Components

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Abstract—**We present a frequency tunable scheme for the gyrotron at millimeter/submillimeter regime. Unlike step-tunable type where oscillation jumps discretely in different transverse modes, this scheme allows a smooth tuning within a single transverse mode using its backward-wave component. The characteristics of backward-wave interaction will be shown. A proof of principle experiment was conducted with a scaled cavity. The result shows the oscillation frequency smoothly transitions over a wide range of 6 GHz from 134 to 140 GHz. The proposed mechanism is capable of producing medium output power with broad frequency tunability up to sub-terahertz region.**

I. INTRODUCTION

The gyrotron oscillators, capable of producing high power in millimeter and sub-millimeter wave region, have widespread applications, for example, heating of the fusion plasmas, measurement of the electron spin resonance (ESR), and the sensitivity enhancement of nuclear magnetic resonance using the dynamic nuclear polarization technique (DNP NMR). The DNP NMR experiment requires a stable continuous-wave (CW) power of several tens of watts at a very high frequency, e.g. 460 GHz and 394.6 GHz. Second cyclotron harmonic interaction is preferred for the much reduced magnetic field requirement. However, the interaction strength of the second harmonic is generally weak, which requires a long interaction structure, resulting in a narrow bandwidth due to high quality factor. Thus the oscillation frequency range is limited and is difficult to meet the DNP NMR experimental requirement. There is a pressing need for gyrotron with frequency tunability.

Gyrotrons with stepwise frequency tunability have been developed for years. The oscillation frequency jumps from one transverse mode to another as the magnetic field is adjusted. Its frequency is basically proportional to the cyclotron frequency or its harmonics, but not continuously tunable. On the other hand, the gyrotron backward-wave oscillator (gyro-BWO) is formed by the internal feedback at a non-resonant structure. The oscillation frequency is tunable, but, to extract the wave power, high performance mode converter must be built, which is extremely difficult at sub-terahertz range.

We propose a scheme to continuously change the oscillation over a single transverse mode as the magnetic field varies. This scheme allows medium power operation with smooth transition in frequency. It is a hybrid system, taking the advantages of the backward-wave interaction (gyro-BWO) and forward-wave output (step-tunable gyrotron). The characteristic of backward-wave interaction will be shown and discussed. A proof of principle experiment was conducted using the Gyrotron FU CW IV in FIR FU. Results verified that this frequency tunable scheme is capable of achieving continuous frequency tuning over a wide range.

The oscillator version of the gyro-devices, based on the feedback mechanism, can be classified into gyromonotron and gyrotron backward-wave oscillator (gyro-BWO). The former is formed by the reflective feedback. The resonant frequency is determined by the resonant frequency of the interaction cavity. So the oscillation frequency is basically fixed. Its tunability is limited by the high quality factor, normally a few thousands. On the other hand, the gyro-BWO is formed by the internal feedback, consisting of the forward moving electron beam and backward propagating wave. The oscillation frequency can be adjusted by either changing the magnetic field or the beam voltage. Broad bandwidth (17%, at X-band) and high efficiency (29.8% at Ka-band) were achieved. However, extracting the wave energy at the upstream section imposes a severe limitation to gyro-BWO, especially at sub-millimeter wave regime.

We suggest a hybrid gyrotron. The wave is extracted at the downstream (advantage of gyromonotron, no mode converter is needed), while the feedback mechanism is mainly internal (advantage of gyro-BWO, broad tuning range). The interaction structure is the cavity type with a reduced quality factor. Table I summarizes the simulation and experimental parameters. In the simulation, the length and the radius of the main interaction section is 2.5 cm and 0.2372 cm, respectively. The upstream end is a cutoff section of 0.4 cm long with a down-taper angle of 2.5°, while the output section is a linear up-taper of 3.0°. Therefore, all the way of excited radiation is directed to the output window.

Figure 1(a) shows the calculated starting currents for two structures, the uniform structure and the mildly tapered structure as shown in the inset. The dashed line is obtained with a uniform section of 2.5 cm. To demonstrate the effect of end reflection, the solid line is calculated using a 2.0 cm uniform section plus a 0.5 cm mild taper of 0.12°. The broader resonant width of HOAMs results in a greater mode overlapping. This self-consistent effect on the starting current has early been found, but it attracts the attention until recent.

It is worth to note here, the starting current for the uniform structure (dashed line) varies dramatically when the magnetic field changes. The ratio between operating current (350 mA) and lowest starting current (22 mA) is 16, which is too high and will cause nonstationary behavior. On the other hand, slightly modified structure (solid line) effectively evens the starting current. The starting current at the lower magnetic field side significantly rises, because of the shorter effective interaction length, while the effective interaction length slightly lengthen at the high magnetic field. The greatest starting current ratio is then reduced to 6.6, which happens to be marginally stable. Another advantage is that the ripple of the starting current is smoothed due to higher mode overlapping. The “traditional” gyromonotron operates at the fundamental axial mode with high quality factor. Transition between axial modes becomes discrete. Each axial mode dominates in

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different magnetic field. The axial mode competition in gyromonotron is quite different from that discovered in gyro-BWO.

Figure 1(b) shows the output power and the oscillation frequency versus the magnetic field for the two structures mentioned in Fig. 1(a). The power of the fundamental mode is, as usual, the largest comparing with other axial modes. The output power basically forms a finger-like shape. The peaks of the output power correlates with resonant condition shown in Fig. 1(a). Noteworthily, in the mode transition region the output power is non-zero and oscillation frequency can be smoothly tuned. The envelope of the lowest output power is still higher than the need for DNP NMR application (a few tens of watts).

The mildly tapered structure (solid line) is superior to the uniform structure (dashed line) in that the neck of the output power (around l=-2) is higher. The mild taper reduces the structure reflection and allows the backward-wave interaction to be dominant. In addition, the mild taper reduces the quality factor, resulting in stronger mode overlapping, which smoothes power spectrum. The velocity spread plays a minor role when the oscillation is close to the waveguide cutoff, e.g. at the lower magnetic field region (l=±1,-2,-3,-4,-5…). Thus, zero spread is used. The crests and troughs in the power spectrum can be further smoothed provided better matching circuit, like the Chebyshev transformer, is used.

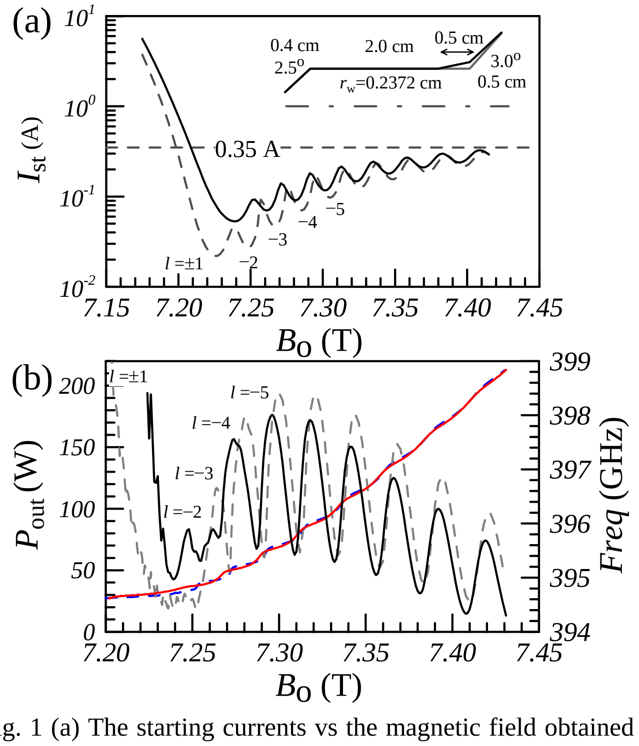

Fig. 1 (a) The starting currents vs the magnetic field obtained with a self-consistent code. (b) The output power and frequency vs the magnetic field at a beam current of 0.35 A. The inset shows two interaction structures, uniform and mildly tapered, not drawn to scale. The results of a uniform cavity are represented in dashed lines and those of a mildly tapered cavity are depicted in solid lines.

Figure 2 shows the experimental results. The output spectrum is plotted in Fig. 2(a) and the oscillation frequency is depicted in Fig. 2(b). In this scaled experiment, two transverse modes are found, TE_{41} and TE_{12}. These two transverse modes are all operated at the fundamental cyclotron harmonic. Each operates at different magnetic field. The transverse-mode competition is less severe. The output power spectrum shows the finger-shape as predicted. The output power of each peak is displayed on the figure. Noteworthily, the frequency is tunable over a broad range of 6 GHz from 134 to 140 GHz. Although the efficiency is low, the experiment verifies the feasibility of the proposed frequency tunable scheme.

In summary, we have demonstrated that a frequency tunable scheme for the gyrotron at millimeter and sub-millimeter wave region is feasible. The electron beam interacts with the backward-wave component. They form an internal feedback loop and allow the oscillation to be smoothly tuned over a broad range. A proof of principle experiment was conducted using a set of scaled parameters and demonstrated a very broad frequency tuning range of 6 GHz (~4.5%). This implies a trade-off between the bandwidth and efficiency which can be exercised in accordance with the specific application need. There is room for efficiency improvement. A detailed research is under way to design a less reflective circuit and to develop a transverse mode selective circuit in the hope of achieving a much higher efficiency and a much broader bandwidth at terahertz region.

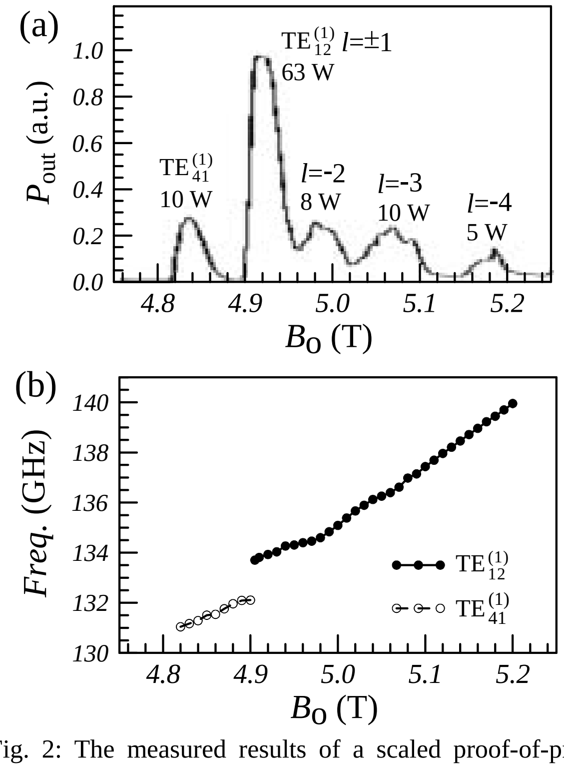

Fig. 2: The measured results of a scaled proof-of-principle experiment. (a) The output power spectrum and (b) the oscillation frequency vs the magnetic field.

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