W-band TE_{01} Gyrotron Backward-wave Oscillator with Distributed Loss

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Abstract—**Distributed wall loss is proposed to enhance the stability and tunability of a *W*-band TE_{01} gyrotron backward-wave oscillator (gyro-BWO). Simulation results reveal that loss effectively suppresses the unwanted transverse modes as well as the high-order axial modes (HOAMs) without degrading the performance of a gyro-BWO that operates at the fundamental axial mode. Linear and nonlinear codes are used to calculate the interaction properties. The effects of the distributed loss on the starting currents of all of the modes of interest are discussed in depth. The interacting structure is optimized for stability. The calculated peak output power is 102 kW, corresponding to an efficiency of 20%. The 3-dB tuning bandwidth is 1.8 GHz, centered at 94.0 GHz when using 5 A and 100 kV electron beam.**

I. INTRODUCTION

The gyrotron backward-wave oscillator (gyro-BWO) is a frequency-tunable source, which can be operated at high frequency and high power. It has advanced greatly in the past few years because an increasing number of applications require frequency tunability, such as, electron spin resonance (ESR), plasma diagnostics, and enhancement of the sensitivity of nuclear magnetic resonance using dynamic nuclear polarization (DNP NMR). The oscillation of gyro-BWO is formed by internal feedback consisting of a forwardly moving electron beam and a backwardly propagating wave. The underlying physics is more complicated than that of resonant feedback, as in gyro-monotron. Contraction of the field profile at nonlinear stage which increases the threshold current of nonstationary behavior were uncovered, enabling a gyro-BWO to operate stably and efficiently at high beam current. On the other hand, the electron transient angle was introduced to define the axial modes at the linear stage and later found that an axial mode with a favorable field profile has been identified commonly to be dominant. Recently, high efficiency operation of 29.8% employing a fundamental waveguide mode TE_{11} was reported at *Ka*-band; and a broadband tuning of 17% was demonstrated using a helical corrugated waveguide at *X*-band. Gyro-BWO has been demonstrated to be highly efficient and broadband, although separately. The next goal is to increase the operating frequency into the low terahertz range, which is associated with a highly over-moded condition. Severe mode competition is the major obstacle.

Figure 1 plots the f-k_z diagram of a uniform interaction structure of radius 1.93 mm. The operating mode is the TE_{01} waveguide mode with fundamental cyclotron harmonic (s=1). The circular TE_{01} mode has the lowest propagating loss of all cylindrical waveguide modes, but it was chosen mainly because the mode converter has been successfully developed and the mode-selective circuit is relatively easy to construct. Major competing modes, for example, TE_{21}, TE_{31}, TE_{02}, TE_{61}, and TE_{32}, are also plotted. The parabolas are waveguide modes and the oblique lines are the beam-wave resonant conditions. The frequency can be tuned by changing either the magnetic field B_0 or the beam voltage V_b. To simplify the notation, an interacting point is represented as $TE_{mn}^{(s)}$, where the sub-indices m and n are the mode indices and the super-script (s) is the cyclotron harmonic number. For example, the operating mode is denoted $TE_{01}^{(1)}$. At the low magnetic field, $TE_{21}^{(1)}$ might be the greatest threat to the operating mode; while at the high magnetic field, $TE_{31}^{(1)}$ is the major competitor. Other second harmonic competing modes include $TE_{02}^{(2)}$, $TE_{61}^{(2)}$, and $TE_{32}^{(2)}$. Luckily, the interaction strengths of the second harmonic are weaker comparing with those of the fundamental harmonic.

In addition to transverse mode competition, however, axial mode competition occurs. The operating mode $TE_{01}^{(1)}$ can be further classified into different axial modes ($\ell = 1, 2, 3...$) based on the concept of the electron transit angle. A mode with a favorable field profile, normally the fundamental axial mode, tends to be the dominant axial mode, which determines the axial mode competition. Recently, the distributed loss was founded to be effective in selectively suppressing the competing axial modes of TE_{11} at the transient state. The distributed loss scheme was adopted to achieve a smooth and stable tuning and the effect of this approach on the suppression of the competing modes was discussed.

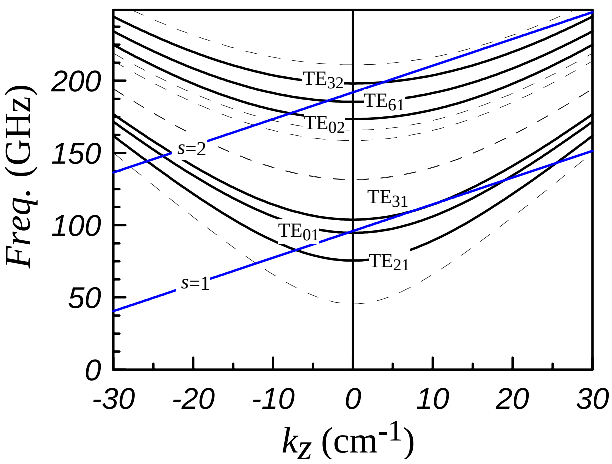

Fig. 1: Frequency vs k_z diagram of a fundamental harmonic TE_{01} gyro-BWO with a waveguide radius r_w of 0.193 cm. The parabolas represent the transverse waveguide modes TE_{mn} and the oblique lines denote the beam-wave resonance lines.

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The distributed wall loss was demonstrated to be an effective means of suppressing spurious oscillations in gyro-TWTs. The major spurious oscillations, caused by the absolute instabilities, are effectively stabilized by coating the distributed loss at the upstream end of the interaction waveguide. This study takes advantage of this fact, but the distributed loss is applied on the downstream wall to stabilize the competing transverse and axial modes. Finally, the nonlinear behavior, the magnetic field and beam voltage tunings at 5 A, are shown.

II. OPTIMIZATION AND NONLINEAR BEHAVIOR

Figures 2(a) and (b) plot the starting current of the modes of interest against the taper length (L_1) and the lossy length (L_2), respectively. In Fig. 2(a), all of the starting currents are inversely proportional to L_1, as expected. A greater taper length L_1 corresponds to more serious mode competition. However, properly tapering the waveguide can enhance the efficiency of the gyro-BWO. A taper section of 1.7 cm is a compromise between mode discrimination and efficiency. Figure 2(b) shows that the lossy section length (L_2) depends only weakly on the starting currents. A length of 0.4 cm is chosen.

In the present configuration, the competing axial and transverse modes are stabilized. Figure 3 plots output power and oscillation frequency as functions of (a) magnetic field B_0 and (b) beam voltage V_b. The calculated results show that the peak output power of the stable $TE_{01}^{(1)}$ gyro-BWO is 102 kW when using 5 A and 100 kV electron beam, corresponding to an efficiency of 20 %. The oscillation frequency can be smoothly tuned. The 3-dB tuning range by the magnetic field is about 1.8 GHz. Figure 3(b) presents the voltage tunings for 3 A, 4 A, and 5 A at B_0 =40.4 kG. Both magnetic and voltage tunings look acceptable.

The competing transverse and axial modes, which limit broadband tuning and high efficiency operation, are stabilized using the distributed loss scheme. Applying the distributed loss in the downstream of an interaction region raises the starting currents of the non-TE_{01} transverse modes by increasing the energy consumption on the lossy wall. It also shortens the feedback loop of the HOAMs ($TE_{01\ell}$, ℓ >1). Properly employing the distributed loss suppresses the competing modes. It is not only useful to the gyrotron traveling-wave amplifier tube (gyro-TWT), but also effective to the gyro-BWO. The calculated results reveal that the *W*-band gyro-BWO is promising. The maximum output power is 102 kW with a 3-dB tuning bandwidth of 1.8 GHz. The experiment is ongoing. The high-performance TE_{01} mode converter is ready, but the magnetron injection gun (MIG) is still being designed.

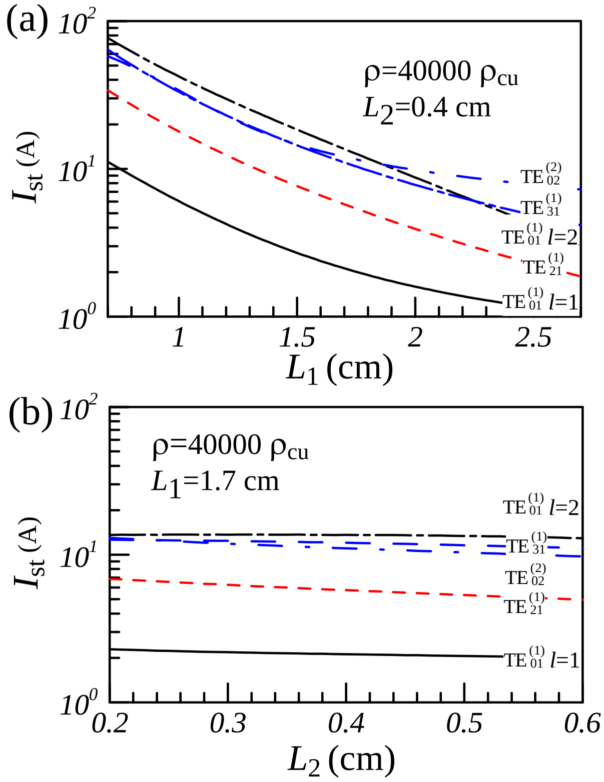

Fig.2 Starting currents I_{st} versus (a) taper section length L_1 and (b) lossy section length L_2. All of the modes of interest are plotted. The tapered structure causes the bulk interaction at the beam entrance, such that L_1 strongly affects the starting current. L_1 and L_2 are determined accordingly.

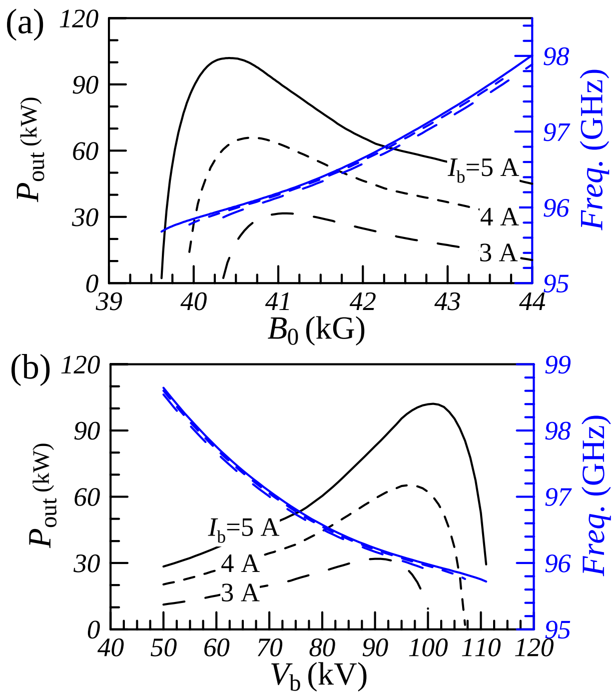

Fig.3 Calculated output power P_{out} and oscillation frequency f vs. tuning parameters: (a) the magnetic field B_0 and (b) the beam voltage V_b.

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