A mode-selective circuit for TE01 gyrotron backward-wave oscillator with wide-tuning range

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This study proposes a mode-selective circuit to suppress the competing modes in a TE01 gyrotron backward-wave oscillator (gyro-BWO). The circuit, also functioning as an interaction structure, comprises of several transverse slices. It eliminates the restrictions of the mode competitions and allows a longer interaction structure to optimize interacting efficiency. Mode-selective effect will be analyzed. Experimental results indicate that the Ka-band TE01 fundamental harmonic gyro-BWO is capable of continuous tuning from 31.4 to 36.4 GHz with a peak efficiency of 23.7%, corresponding to 100 kW at \(I_b=4.5\) A and \(V_b=93.6\) kV. © 2009 American Institute of Physics.

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A gyrotron backward-wave oscillator (gyro-BWO), based on the electron cyclotron maser, is a frequency-tunable, high-power, coherent millimeter-wave source. The properties of gyro-BWO have been theoretically studied and experimentally demonstrated. The continuous frequency tuning by varying the magnetic field or the beam voltage in a nonresonant structure has generally been evidenced with fundamental mode operation [rectangular TE10, cylindrical TE11, and helical corrugated TE11/TE31 (Refs. 4 and 5)]. As interest in the terahertz-wave regime grows, the operation of gyro-BWO in high-order mode is preferred due to the power-handling capability. The severe transverse mode competition arises because the separation between the cutoff frequencies of adjacent transverse modes decreases as the order of the mode increases.

Figure 1 plots the frequency-\(k_z\) diagrams of the 11 lowest TE modes and the fundamental (\(s=1\)) as well as second (\(s=2\)) cyclotron harmonic beam-wave resonance lines for a TE01 mode, fundamental harmonic, Ka-band gyro-BWO. Oscillation occurs at the intersection of the waveguide mode curve and the beam-wave resonance line. The beam-wave coupling strength for a transverse mode is strongly related to the electron guiding center \(r_c\). When \(r_c\) is set to the position of strongest coupling for the TE01 fundamental harmonic interaction (denoted as TE(1)01), the potential parasitic oscillations are TE(1)21, TE(1)31, TE(1)12, and TE(1)02. Based on the coupling strength, TE(1)21 and TE(1)31 modes are detrimental in the lower and higher magnetic tuning regions, respectively. The stable tuning region is shrunk greatly. The competing behaviors of TE01 gyrotrons have experimentally explored.

To effectively suppress unwanted oscillations, several mode-selective circuits have been developed. A slotted structure was utilized on a TE31 third-harmonic gyrotron traveling wave tube (gyro-TWT) amplifier. An axially sliced interaction circuit, which interrupts the wall current of the unfavorable mode, was developed for TE21 second harmonic gyro-TWT and provided a very high output power (207 kW at 15.7 GHz). A helical corrugated structure, which changes the dispersion relation and operates with hybrid modes, reportedly supports broadband on gyrotrons.\(^{4,5,11}\) To date, however, no attempt has been made to design a mode-selective circuit for TE01 mode gyro-BWO.

This investigation presents a transverse sliced interaction structure for the TE01 gyro-BWO. Since the wall surface current for the TE01 mode is in the azimuthal direction only, the TE01 wave is almost unaffected as it travels through the transverse slice. In contrast, the competing modes with axial surface currents are significantly affected. Mode-selective effect is analyzed using the high-frequency structure simulator.

A steady-state, particle-tracing, self-consistent code\(^{1}\) is employed to evaluate the performance of the operating mode and the starting behaviors of all potentially competing modes.

![FIG. 1. (Color online) Frequency vs \(k_z\) diagrams for waveguide TE modes and beam-wave resonance lines (s denotes the cyclotron harmonic number). Parameters are waveguide radius \((r_c)=0.58\) cm, beam voltage \((V_b)=100\) kV, velocity ratio \((\alpha=v_e/v_i)=1.1\), and magnetic field \((B_0)=13.5\) kG.]

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The magnetron injection gun (MIG) was developed for the TE\(_{11}\) Ka-band experiment (\(r_0=0.09\) cm). To modify the MIG in favor of TE\(_{11}\) interaction at Ka-band, the ordinary concentric electron beamlet is offset by a distance \(r_0\) of 0.28 cm, and thus the offset guiding center \(r_s^\prime\) ranges from 0.19 to 0.37 cm. The velocity ratio (pitch \(\alpha\)) of the MIG gun declines as the magnetic field increases. The relevant function is

\[
\alpha = \left[1 + \alpha_{\text{ref}}^2 \left(\frac{B}{B_{\text{ref}}} \right)^2 - 1\right]^{-1/2}.
\]

The pitch \(\alpha\) is presumed to 1.2 (\(\alpha_{\text{ref}}\)) at a reference magnetic field of 13 kG (\(B_{\text{ref}}\)). It decreases as \(B_0\) increases, significantly limiting the 3 dB tuning bandwidth, as will be discussed in the experimental section.

Figure 2(b) plots the starting current \((I_s)\) as a function of \(B_0\) for all of the modes of interest. The \(I_s\) of TE\(_{21}\) and TE\(_{31}\) fundamental \((l=1)\) and second axial modes \((l=2)\) are well below the operating current of 5 A. Moreover, the starting threshold of operating mode is higher than that of competing modes in the regions \(B_0<14.2\) kG and \(B_0>16.5\) kG. Without a mode-selective circuit, severe mode competitions are expected in this configuration. The dominant mode is difficult to predict from the starting behaviors and should be analyzed from start-up scenarios. Notably, the TE\(_{02}\) mode, the most competitive mode in TE\(_{01}\) gyro-TWT, is not a threat when the system is operated at backward-wave region.

Figure 3(a) depicts the cross-sectional view of a representative structure for a single transverse slice. The copper cylindrical shell with outer radius \(r_s\) and inner (waveguide) wall radius \(r_w\) is divided into two parts and separated by a distance of \(\Delta L\). As the wave propagates through the slice, the coupling wave is induced and travels toward the terminal boundary. Either a heavy load or an open boundary can be used to terminate the coupling wave, and the latter is adopted in our system. Therefore, the coupling wave power partially diffracts into the space and is partially reflected. Multiple reflections occur between the boundaries of \(r_s\) and \(r_w\), causing the slice to behave as an open resonator. The resonant frequency depends on the reflection coefficients and the reflection loop \((r_s-r_w)\). The loss factor \((F_{\text{loss}})\), defined as the total power loss normalized to the input power \((P_{\text{loss}}/P_{\text{in}})\), is introduced to specify the mode-selective effect. The loss factor is maximum at the resonant frequency, and the maximum values for the TE\(_{21}\), TE\(_{31}\), and TE\(_{41}\) modes are all about 0.4 [Fig. 3(b)], which means 40% of the wave power of a competing mode is absorbed by a single transverse slice. The loss factor for the operating TE\(_{01}\) mode is two orders of magnitude lower than those of the competing modes and is negligible. The TE\(_{02}\) has similar characteristics to the TE\(_{01}\) mode and is also less affected. Numerous transverse slices with various resonant frequencies could be combined to achieve an intensive and broadband suppression.

Figure 4(a) displays the integrated rf structure. The elec-
electron beam passes through an offset tube and becomes an off-axis beam in favor of TE$_{01}$ interaction. This tube is upshifted by a spacer with a thickness of 2.8 mm. The whole interaction length was divided into six parts by five transverse slices. Figure 4(b) shows the design and the finished parts. The pins and corresponding holes on two connecting parts were precisely aligned. An O-ring was employed to seal the vacuum for each transverse slice. As shown in Fig. 4(b), four-pin and six-pin setups are designed better to suppress TE$_{21}^{(1)}$ and TE$_{31}^{(1)}$ modes, respectively. The generated backward wave is extracted by a high-performance Y-type TE$_{01}$ mode converter.

Figure 5(a) depicts the interaction structure with transverse slices. In comparison to Fig. 2(a), an additional cutoff section, whose sidewall is coated with heavy losses, is incorporated into the collector end. Based on MIG simulations, Fig. 5(b) plots the simulated velocity ratio and axial velocity spread as functions of magnetic field. Figure 5(c) shows the interacting efficiency and the corresponding frequency for magnetic field tuning. Both the simulations (dashed lines) and the experimental results (symbols) are displayed. The measured peak efficiency of TE$_{01}$ gyro-BWO with the mode-selective circuit is 23.7%, corresponding to 100 kW at 31.55 GHz, $B_0=13.55$ kG, $I_b=4.5$ A, and $V_b=93.6$ kV. An extremely wide range of continuous tuning from 31.4 to 36.4 GHz (15.8%) is achieved. The 3 dB tuning bandwidth (0.75 GHz, 2.3%) is narrow due to the decline in pitch $\alpha$. The output signals, diagnosed by the oscilloscope and the spectrum analyzer, are stable and free from parasitic oscillation. As the beam power increases, however, nonstationary behaviors were observed in a part of the tuning region. The experimental results that are shown in Fig. 5(c) agree closely with theoretical predictions.

In summary, the tunability of a TE$_{01}$ gyro-BWO in the Ka-band was verified experimentally, and the high efficiency (23.7% at 100 kW output power) was demonstrated under the pulse operation ($\sim$1 $\mu$s). The mode-selective circuit, with the transverse sliced structure, effectively suppresses the major competing TE$_{21}^{(1)}$ and TE$_{31}^{(1)}$ modes and is harmless to operating TE$_{01}^{(1)}$ mode. This mechanism can also be applied to other gyrodevices to suppress severe mode competition.

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