Gyrotron Traveling Wave Amplifier with a Helical Interaction Waveguide

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A new microwave system in the form of a cylindrical waveguide with a helical corrugation of the inner surface is proposed for a gyrotron traveling wave tube (gyro-TWT). The corrugation radically changes the wave dispersion in the region of small axial wave numbers. This allows significant reduction in the sensitivity of the amplifier to the electron velocity spread and an increase in its frequency bandwidth. An X-band gyro-TWT operating at the second cyclotron harmonic with a 200-keV, 25-A electron beam produced an output power of 1 MW, corresponding to a gain of 23 dB and an efficiency of 20%. [S0031-9007(98)07974-5]

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The gyrotron traveling wave tube (gyro-TWT) [1,2] is an established amplifier variant of the broad class of gyrodevices. In this device electrons move along helical trajectories inside a waveguide, immersed in a uniform magnetic field $\vec{H}_0 = H_0\vec{z}_0$. Because of the dependence of electron cyclotron frequency, $\omega_H = eH_0c^2/E$, on electron energy E, the particles, which are influenced by a wave, are rotating with different frequencies and gather into azimuthal bunches. When the phase of the bunches are correct, they are able to amplify the wave effectively. An important advantage of the gyro-TWT, allowing its operation at shorter wavelengths compared to the "usual" Cherenkov-type TWT's, is their ability to amplify fast waves which are not localized near a microwave structure (e.g., waves of smooth waveguides). For this reason the gyro-TWT has attracted significant attention [3–5].

As a rule, a smooth cylindrical metal waveguide has been used as the microwave system of gyro-TWT's. In order to increase the frequency band, one usually operates at grazing incidence where the beam dispersion overlaps with the wave (the axial electron velocity is close to the group velocity of the wave). For subrelativistic electron energies (50–100 keV) the beam dispersion line intersects with the wave curve close to cutoff making the interaction susceptible to spurious gyrotron oscillations which can be easily excited at the low-frequency boundary of the amplification band where the axial wave number and group velocity are small. On the other hand, at the high-frequency boundary of the amplification band the axial wave number of the operating wave is rather large leading to a significant Doppler broadening of the cyclotron resonance line and a decrease in efficiency because of spread in the axial electron velocity. For these reasons subrelativistic gyro-TWTs have significantly lower efficiency than gyrotrons.

For relativistic axial electron velocities the regime of grazing is far from cutoff and axial wave numbers are even larger than in the subrelativistic case. Therefore, the Doppler frequency shift is very important and such a gyro-TWT does not differ from the so-called cyclotron autoresonance maser (CARM) (see, e.g., [6,7]). This regime is attractive for high-frequency radiation production, but like free electron lasers and unlike the gyrotron it is very sensitive to the spread in electron velocity.

Thus, the unfavorable dispersion of the cylindrical waveguide in conventional gyro-TWT's increases their sensitivity to the spread in axial velocity resulting in low interaction efficiency which is a significant limitation to their further development. The most favorable wave dispersion for a gyro-TWT is when the wave group velocity is constant and equal to the electron axial velocity in the region of close-to-zero axial wave numbers. As shown in [8,9], the necessary dispersion may be realized, over a rather broad frequency band, in an oversized circular cylindrical waveguide with a helical corrugation of the inner surface:

$$r(\varphi, z) = r_0 + l\cos(\overline{m}\varphi + \overline{h}z), \qquad (1)$$

where r, φ, z are cylindrical coordinates, r_0 is the waveguide mean radius, l, $\overline{m}$, and $\overline{h} = 2\pi/d$ are the amplitude, azimuthal, and axial numbers of the corrugation, respectively, and d is the corrugation period. The desired change of the dispersion will be achieved if the corrugation couples two partial rotating waves of a waveguide with a radius of r_0; one partial wave is near cutoff, mode (A), and has a small axial wave number $h_A \ll k$, where $k = \omega/c$, while the other partial wave, a traveling wave (B), has a large axial wave number, $h_B \sim k$. For such conditions to be realized, the axial wave numbers and azimuthal indices of the waves and the corrugation should satisfy the Bragg conditions

$$h_B \approx \overline{h}, \qquad m_A + m_B = \overline{m}. \qquad (2)$$

The resonant coupling of the waves corresponds to the intersection of their dispersion curves or, more exactly, the intersection occurs between the mode A and the first spatial harmonic of the wave B with cutoff frequencies ω_0 and ω_{0B}, respectively (Fig. 1).

A similar helical corrugation which scatters the operating near cutoff mode into a traveling wave resulting in one-way output from the cavity has also been used in gyrotrons [10]. In Ref. [11] the use of a helix mounted into the cylindrical conducting waveguide for improvement of a gyro-TWT wave dispersion has been discussed.

If the corrugation amplitude l is small compared with the wavelength, the field structure and dispersion characteristics of a helical waveguide can be calculated by means of the method of perturbation [12–14]. The eigenwaves $W_\pm$ and W_1 (Fig. 1), which arise as a result of coupling the partial waves A and B, can then be found. When parameters of the corrugation are properly chosen, the wave W_1 has the desirable dispersion. The frequency gap between W_1 and "spurious" waves $W_\pm$ in the region of "zero" axial wave numbers is of the order of the coupling coefficient of the waves σ, which is proportional to the relative amplitude of the corrugation l/r_0 and depends also on the azimuthal and radial indices of the partial waves [12–14]. For a relatively small corrugation depth, when $\sigma \leq 0.1$, the method of perturbation provides good agreement with "cold" experiments.

When using the helical waveguide as the microwave system of a gyro-TWT, it is advantageous to have an amplification parameter C, which is proportional to $I^{1/3}$ (I is the electron current), much smaller than the coupling coefficient σ. Under these conditions, $C \ll \sigma$, the electron beam does not significantly alter the dispersion characteristics, and the electrons can be coupled with the cold eigenwave W_1 as shown in Fig. 1. The attractive dispersion relation as represented in Fig. 1 can be obtained by tuning the magnetic field for the synchronism $\omega_1 - h_1 v_\| \approx s\omega_H$ (here s is the cyclotron harmonic number) between the desirable wave with frequency ω_1 and axial number h_1 and the electrons moving with axial velocity $v_\|$. For this situation, the fifth-order dispersion equation of a helical gyro-TWT can be reduced to a third-order equation

$$(h - h_1)[h - (\delta - \Delta_H)/\beta_{\|_0}]^2 = \hat{C}^3\{1 + (2s\beta_{\|_0}/\beta_{\perp_0}{}^2)[h - (\delta - \Delta_H)/\beta_{\|_0}]\}, \quad (3)$$

which is identical to that for a conventional gyro-TWT with a smooth waveguide [1]. h and h_1 have been normalized to $k_0 = \omega_0/c$. $\delta = (\omega - \omega_0)/\omega_0$ and $\Delta_H = (s\omega_H - \omega_0)/\omega_0$ are the normalized frequency and magnetic field mismatches, respectively, $\beta_{\|_0} = v_{\|_0}/c$ and $\beta_{\perp_0} = v_{\perp_0}/c$ are the normalized axial and transverse electron velocities, respectively, and $\hat{C} = C(\chi/2)^{1/3}$ is the modified amplification parameter of the wave. The coefficient $\chi = 2(h_1 + \Delta_g - \delta/h_0)/[3h_1^2 + 2h_1(\Delta_g - \delta/h_0) - 2\delta]$ is responsible for the content of the resonant partial mode A in the operating eigenwave W_1, where $\Delta_g = \bar{h} - h_0$ and $h_0 = |h_B(\omega_0)|$ are also renormalized to k_0 [9]. In Eq. (3) h_1 is a function of δ and describes the cold dispersion of the operating eigenwave of the helical waveguide. For the usual gyro-TWT $\chi = 1/\beta_{\mathrm{gr}}$, where β_{gr} is the normalized group velocity in a smooth waveguide.

The analysis of Eq. (3) shows that for a large region of electron parameters, including subrelativistic and relativistic energies, a very-broad frequency-band gain can be obtained by optimizing the parameters of the corrugation and the value of the magnetic field. A good agreement between solutions of the simplified Eq. (3) and a more exact fifth-order equation up to $\sigma \sim C$ demonstrates the correctness of the approach of the dominant interaction of electrons with the eigenwave of the cold system. This approach allows a similar simplification of the nonlinear analysis which can be performed using the equations of the usual gyro-TWT with changed dispersion $h_1(\omega)$ and coefficient χ.

It is clear from the helical gyro-TWT dispersion curves (Fig. 1) that mode $W_\pm$, having a region with a small group velocity, can be easily excited like an operating mode of a conventional gyrotron-oscillator. But for attractive amplification regimes, when the corrugation is sufficiently deep, a large separation of curves W_1 and $W_\pm$ occurs, the mode $W_\pm$ can still be excited but at magnetic fields significantly higher than the operating values. The numerical analysis shows that it is possible to operate the amplifier without self-excitation, with a high gain (30–35 dB) and electronic efficiency (30%–35%) over a very broad frequency band (15%–20%), even when the electron beam has a large transverse velocity spread up to 40%. In order to check these predictions an experiment at the high-current direct-action accelerator at the University of Strathclyde was carried out.

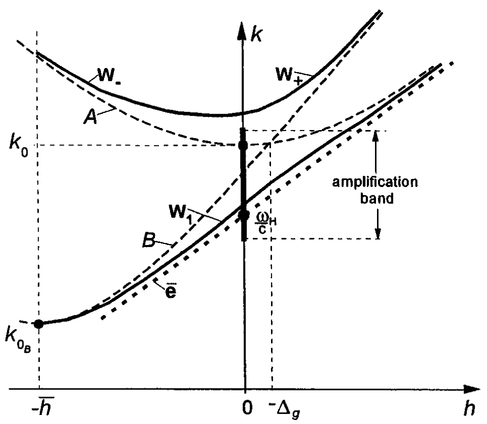

FIG. 1. Dispersion diagram for a helical waveguide: A, B: The partial near cutoff and traveling waves of a smooth waveguide, respectively, which are coupled due to the helical corrugation of the inner surface; W_1 and $W_\pm$: The operating and "spurious" eigenwaves of the helical gyro-TWT; $\bar{e}$: Unperturbed electron cyclotron wave.

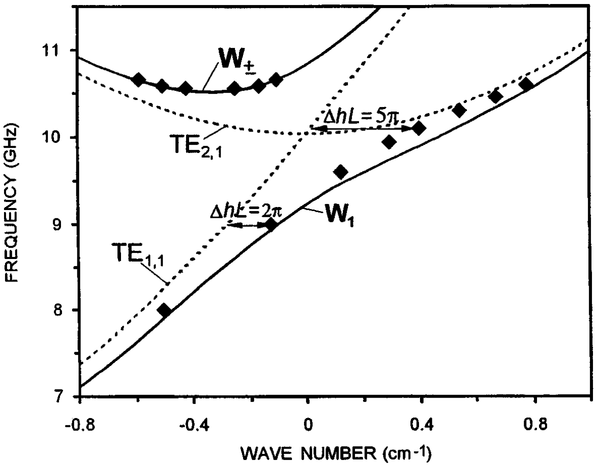

FIG. 2. Disperson diagram for the operating helical waveguide: Dotted and solid lines correspond to partial and eigen modes, respectively; (◆): results of "cold" measurements.

In order to enhance the mode selection a thin electron beam encircling the waveguide axis was used. Such a beam can excite only resonant modes with azimuthal indices equal to the cyclotron harmonic number, $m_A = s$. Choosing the far-from cutoff $\mathrm{TE}_{1,1}$ wave as partial wave B and the near cutoff mode $\mathrm{TE}_{2,1}$ as the partial mode A the interaction at the second cyclotron harmonic, $s = 2$ was studied. In this case, a three-fold helical corrugation, $\overline{m} = 3$, has to be used for effective resonant coupling of these modes and for providing the necessary eigenwave dispersion. It is important to note that in this case the operating magnetic field was so low that spurious fundamental gyrotron excitation of a $\mathrm{TE}_{1,1}$ mode was impossible, while gyrotron excitation at higher cyclotron harmonics can lead to some problems. A 40 cm long waveguide of 14.5 mm mean radius with a helical corrugation of 1.5 mm amplitude and 37.5 mm period was tested in "cold" and "hot" experiments. To obtain the cold dispersion of the operating wave W_1, the angle of rotation for the linearly polarized $\mathrm{TE}_{1,1}$ wave which passed through the helical waveguide (similar to the Faraday effect in optical media) was measured. The points with phase difference $\Delta hL = n\pi$ between the rotating waves of opposite rotation, where L is the waveguide length, $n = 1, 2, \ldots$, and, correspondingly, the polarization vector at the output of the waveguide perpendicular or parallel to the initial wave, are shown in Fig. 2. In order to find the dispersion curve $W_{\pm}$, resonant frequencies for longitudinal modes $p = 1, 2, 3\ldots$ of the cavity, were measured.

For the operating amplification regime, the driving RF signal was produced by one of two pulsed magnetrons with operating frequencies of 9.4 and 9.2 GHz, maximum power of 25 kW, and pulse duration of 1 μs. Nearly 50% of the magnetron power was transported through a long rectangular waveguide to a specially designed broad frequency-band launcher (Fig. 3) which was 90% efficient. This circular section supported only the fundamental $\mathrm{TE}_{1,1}$ mode for the operating frequency. Its radius was then adiabatically increased to the radius of the interaction region. A linearly polarized wave was injected into the helical waveguide, of which half of the incident power, with the correct rotation of the electric-field vector, participated in the interaction. Therefore, the maximum input power in the operating eigenwave of the helical waveguide was approximately 5.5 kW. It is important for gyro-TWT operation at frequencies below cutoff of the mode $W_{\pm}$ that all the output power is contained in the wave W_1 which is then easily transformed into a $\mathrm{TE}_{1,1}$ mode and radiated in a nearly Gaussian wave beam. The output power was measured using attenuators and sensitive semiconductor detectors, calibrated with the magnetron. Cutoff waveguide filters were also used for measuring the radiation frequency.

A 200 keV/25 A rectilinear electron beam with a diameter of 8 mm and FWHM duration of 150 ns (Fig. 4) was produced from a "cold" velvet cathode (Fig. 3). A

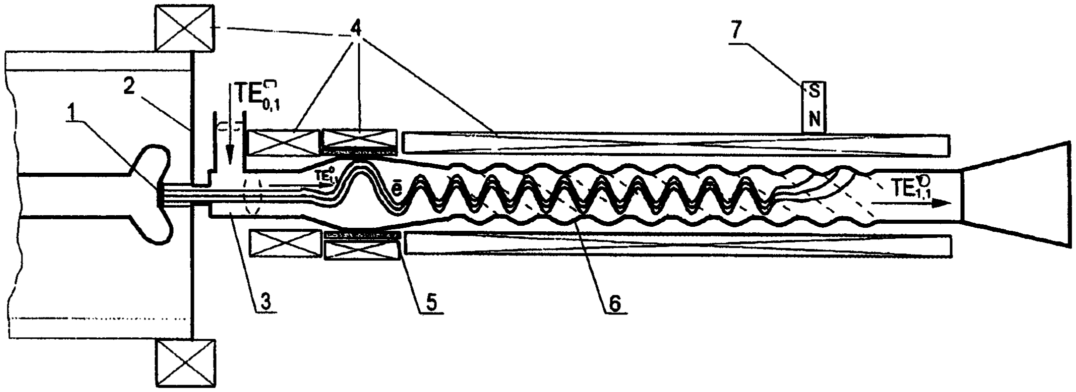

FIG. 3. Schematic diagram of the gyro-TWT with a helical waveguide: 1: Velvet cold cathode; 2: anode; 3: wave launcher (converter of $\mathrm{TE}_{0,1}$ mode of a rectangular waveguide into $\mathrm{TE}_{1,1}$ mode of a circular waveguide); 4: coils generating dc guiding magnetic field; 5: kicker; 6: operating helical waveguide; 7: deflecting magnet.

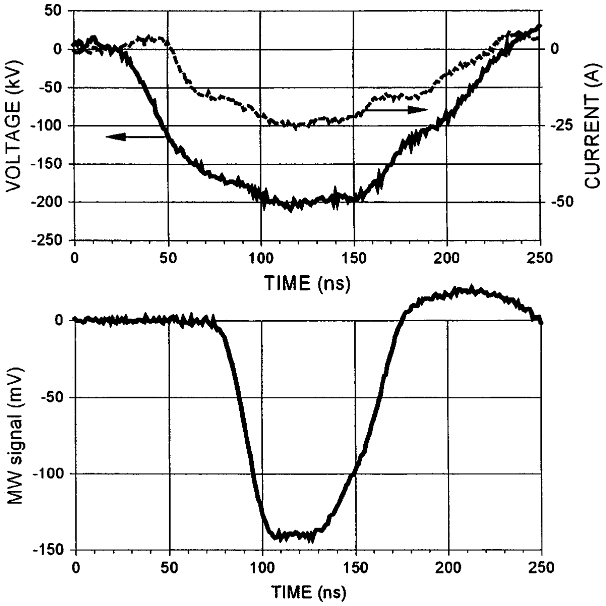

FIG. 4. Oscilloscope traces of voltage, beam current, and microwave signal.

transverse velocity $\beta_{\perp_0} = 0{-}0.6$ was imparted to the electrons in a dc single-period bifilar spiral kicker 4.5 cm in diameter with a current variable from 0 to 100 A. The electron velocities and their spreads were estimated experimentally from the imprints of the beam on a scintillator placed at different distances from the kicker. For the operating transverse velocity $\beta_{\perp_0} = 0.5{-}0.6$ a large spread in axial velocity of about 30% was measured. Numerical simulations predict for the helical gyro-TWT with the above parameters an efficiency of $\sim 30\%$ and a 3 dB frequency bandwidth of $\sim 10\%$ (for a deeper corrugation the bandwidth can be widened up to 20%–25%).

In "hot" experiments at the operating magnetic field of 0.22 T the transverse electron velocity was limited to a value of $\beta_{\perp_0} = 0.5$ because of self-excitation of the mode of operation as observed by oscillations at frequencies 10–10.5 GHz where the wave reflection coefficient from the input was relatively high. Therefore, in the regime of zero-drive stability the achievable amplification and power are slightly less than the calculated values for the saturation regime. It is important to note that when the parasitic oscillations were close to their starting regime they were easily suppressed if the magnetron was switched on.

To study the amplification regimes of the helical gyro-TWT, the values of the guiding and kicker magnetic fields, the input rf power and the length of the electron-wave interaction were systematically changed. The saturation of the amplification was not observed due to a combination of factors, namely the parasitic self-excitation of the mode of operation limited the electron transverse velocity and/or the length of the interaction region, and the input rf power was a little too low. For both operating frequencies of the magnetrons, 9.4 and 9.2 GHz, and fixed parameters of the electron beam and magnetic field the same output power was measured. A very important measurement with the use of elliptical waveguide polarizers in front of the microwave detection system confirmed that the output wave $TE_{1,1}$ had a circular polarization with a rotation opposite to the electron rotation in the magnetic field. In the regime of single-frequency amplification, the gyro-TWT provided a maximum output power of 1 MW, a gain of 23 dB and an efficiency of 20%.

Further experiments are now in progress at the Institute of Applied Physics, Nizhny Novgorod, Russia and at the University of Strathclyde, Glasgow, UK.

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