Gyro-Traveling-Wave Tubes

12.1 Historical Introduction

Pantell (1959) and Gaponov and his group (1959) carried out the first experimental studies of the interaction of gyrating electrons with fast traveling waves. At that time, R. H. Pantell reported the results of his experiments in which the radiation at frequencies between 2.5 and 4.0 GHz was obtained due to the interaction between the cyclotron wave and the backward $TE_{11}$-wave of a rectangular $S$-band waveguide. The power achieved was about 0.4 W and the corresponding efficiency was 0.5%. That device operated as an oscillator whose starting current was about 100 mA. So, according to our nomenclature discussed in Chapter 1, it should be considered as a CRM-BWO rather than a CRM-TWT.

A. V. Gaponov (Gaponov et al. 1959c) reported the first results of the studies of a CRM-TWT. In his unpublished experiment, in which a beam of electrons gyrating in a constant magnetic field amplified the $TE_{10}$-wave of a rectangular waveguide, a so-called electronic gain has been demonstrated. The term "electronic gain" needs some explanations. In that experiment the output power was lower than the input power. However, as was discussed in Chapter 6, due to insertion losses (see (6.34) and (6.35)), only one-third of the input power is coupled to the growing wave at the waveguide entrance. Therefore the fact that the output power exceeded $P_{in}/3$ allowed researchers to conclude that in this experiment an amplification of a forward EM wave by a beam of electrons gyrating in a constant external magnetic field has been observed. This and later experiments were, however, quite discouraging in the sense that the efficiency observed was much lower than that predicted by the theory. It soon became clear that the axial velocity spread inherent in the beams of electrons gyrating in a constant external magnetic field causes...
significant Doppler spread of resonant frequencies in the case of electron interaction with traveling waves (Flyagin et al. 1977, Andronov et al. 1978). Therefore, in the mid-1960s, much better progress was demonstrated in the experiments with trochoidal electron beams. (This issue was already discussed in Sec. 2.1.)

Later, development of gyrodevices in the USSR was focused on the gyrotron oscillators and gyroklystrons, although theoretical studies of gyro-TWTs have been continued. The development of gyro-traveling-wave tubes (gyro-TWTs) was actively started in the United States in the late 1970s, first, by the researchers from the Naval Research Laboratory (NRL) and a little later by Varian. After detailed theoretical studies, researchers at NRL demonstrated successful experimental operation of a wide-band, Ka-band gyro-TWT (Barnett et al. 1981).

The first Varian gyro-TWT operated at 5 GHz at more than 100 kW peak power level (Ferguson, Valier, and Symons 1981). Symons and Jory (1981) described the first stage of these experiments in detail in a review paper. Also, Hirshfield and Granatstein (1977) described in detail the first experiments on amplification of forward EM waves by gyrating beams of relativistic electrons, which took place in the 1970s. (This issue will be discussed in more detail in the next chapter, in the section on CARMs.) In the early 1980s, a W-band gyro-TWT had been developed at Varian (Eckstein, Latshaw, and Stone 1983). Parameters of this tube can be found in Table 6.2 in Barker and Schamiloglu (2001).

Successful development of gyro-TWTs has been continued in many laboratories for over 20 years. Some results of this development are presented below.

### 12.2 Large-Bandwidth Gyro-TWTs

It is well known that, although it is always desirable to have all performance characteristics of any device superior, in real life a tendency to improve one performance characteristic causes degradation of another. Therefore, there is always a trade-off between tendencies to improve various performance characteristics, and priorities in improving these characteristics are dictated by a given application of a device. Although at present there are no systems in which gyro-TWTs are used, one can easily envision that the focus of the gyro-TWT development could be made either on achieving the largest possible bandwidth (in the case of their use in communication systems), or on gain enhancement. The latter can be the case of the gyro-TWT used in radar systems.
where a moderate bandwidth exceeding the bandwidth of gyro-klystrons should be accompanied with a high enough gain for realizing the maximum gain-bandwidth product. In this section we will consider large-bandwidth gyro-TWTs.

The largest bandwidth obtained in gyro-TWTs with the uniform interaction waveguide and external magnetic field was reported by Chu et al. (1990). In that Ka-band experiment an orbital-to-axial velocity ratio of electrons was rather low (about 0.8), which resulted in the stabilization of operation and allowed researchers to realize the bandwidth in excess of 10% in the large-signal regime.

The first time an understanding of the fact that simultaneous tapering of the waveguide and external magnetic field may result in significant enlargement of the bandwidth of gyro-TWTs was possibly expressed in a general form by Bratman et al. (1973). Nevertheless, a simple concept of a single-stage, wide-band tapered gyro-TWT was first proposed and analyzed by Y. Y. Lau and K. R. Chu (Lau and Chu 1981). These authors proposed to use an up-tapered waveguide as an interaction circuit and to taper an external magnetic field in such a way that a grazing condition for the waveguide mode and the cyclotron wave, which was discussed in Chapter 6, is locally fulfilled everywhere along the waveguide. A schematic drawing of such a circuit is shown in Fig. 12.1. As is seen in the figure, the authors proposed to introduce a signal in the reverse direction as a backward wave, which should be reflected from the cutoff cross section. Then, such a reflected wave starts the resonance

![Fig. 12.1. Schematic drawing of a tapered wide-band gyro-TWT. (Reproduced from Lau and Chu 1981)]
interaction with electrons as a forward wave. (An alternative side-wall injection scheme, which is more suitable for high gain operation, was discussed by Chu et al. 1981.)

This concept was immediately verified in the proof-of-principle experiment (Barnett et al. 1981), where a 13% bandwidth in the range of frequencies from 32.5 GHz to 38.0 GHz was achieved at the multi-kW peak power level with the gain close to 20 dB and efficiency about 13%. In this experiment the TE$_{01}$ circular electric mode was used. The waveguide was linearly up-tapered from a radius of 4.57 mm to 6.22 mm at a distance of 33.3 cm. In addition to the main superconducting solenoid, two independent trim coils were used to properly taper the profiled magnetic field. It is worthy of mentioning that this tapering of the magnetic field has led to substantial enhancement of the gain, which was about a few dB only in the constant magnetic field. It was also shown that the operation of tapered gyro-TWTs is more stable than that in gyro-TWTs with constant parameters of the circuit because the length of the interaction space is shorter, and therefore the start-oscillation current of the absolute instability is higher.

Some improvements in the design allowed researchers from NRL to increase the instantaneous bandwidth of the Ka-band tapered gyro-TWT to 33% with a small-signal gain in excess of 20 dB and efficiency of about 10% (Park et al. 1994). However, window reflections in combination with the use of the signal injection scheme shown in Fig. 12.1 resulted in a round-trip pass for the amplified radiation at any frequency that caused severe limitations on the achievable gain.

The next conceptual step in the development of large-bandwidth gyro-TWTs was made at NRL when the concept of a two-stage tapered gyro-TWT shown schematically in Fig. 12.2 was analyzed theoretically (Ganguly and Ahn 1982).

![Fig. 12.2. Schematic of a tapered, two-stage gyro-TWT. (Reproduced from Ganguly and Ahn 1982)]
1982) and verified experimentally (Park et al. 1995). To some extent, this work was also initiated by the paper (Moiseev 1977) in which the bandwidth of such a device was studied analytically. (Later, Nusinovich and Walter 1999 explained this analytical approach in more detail.)

Such a Ka-band gyro-TWT operated with the small-signal gain of 30 dB and saturated gain of 25 dB over a 20% bandwidth with the efficiency of 16% and output power of about 8 kW. The device was driven by a 1.5 A, 33 kV electron beam with a relatively small orbital-to-axial velocity ratio (about 0.7) and low axial velocity spread (about 4%). Low voltage allowed researchers to operate reasonably close to cutoff, which made the operation relatively insensitive to the velocity spread. A small orbital-to-axial velocity ratio made the device operation more stable with respect to spurious self-excitations.

Recently, a new concept of large-bandwidth gyro-TWTs has been actively studied by a joint group of researchers from the Institute of Applied Physics (Nizhny Novgorod, Russia) and the University of Strathclyde (Glasgow, U.K.) (Denisov et al. 1998, Cooke and Denisov 1998). This concept is based on the use of a cylindrical waveguide having a helically grooved wall. Such a helical corrugation of the inner surface of the waveguide is designed to selectively couple one wave excited at a frequency close to cutoff to another, lower-order wave that propagates at a small Brillouin angle with respect to the waveguide axis. This coupling of two waves due to the periodic waveguide wall perturbations is essentially the same as one discussed in Sec. 10.2: again, the periodic corrugation given by (10.1) couples the waves whose azimuthal indices and axial wave numbers obey Bragg resonance conditions given by (10.2) and (10.3). In a gyro-TWT with such a helically grooved waveguide, electrons can interact with the wave excited near cutoff frequency, which makes the device operation relatively insensitive to the axial velocity spread. Also, a group velocity of a normal wave of such a structure can be more or less constant over a wide frequency band.

Note that initially such a concept of using a helix corrugation for transforming a wave excited near cutoff into a traveling wave was proposed by M. I. Petelin and I. M. Orlova in the late 1960s (Orlova and Petelin 1968) with regard to gyrotron oscillators. (Later, Goldenberg, Nusinovich, and Pavelyev 1980 continued the treatment of this concept.) The driving idea was to directly transform the operating mode into a wave suitable for transmitting with small losses through long waveguides. It was also taken into account that such wave coupling should reduce the diffractive Q-factor of the mode, and hence lower the ohmic losses in the cavity walls, which is important for high-power tubes operating in the CW regime. However, just the fact that the Q-factor of
the operating mode will be reduced while Q-factors of parasitic modes will remain unchanged made this mode less competitive. Thus, the use of this idea in high-power gyrotrons with a dense spectrum of competing modes looked unrealistic; therefore, this concept had not been studied for a long time until it was revived with regard to gyro-TWIs.

Recently, Bratman et al. (2000) verified the bandwidth capabilities of such a gyro-TWT with a helically corrugated waveguide experimentally. In this experiment, the operating mode was formed by a coupling of the $\text{TE}_{2,1}$-wave to the counterrotating $\text{TE}_{1,1}$-wave. A corresponding dispersion diagram is shown in Fig. 12.3. The upper boundary of the amplification band shown in this figure is determined by the presence of parasitic waves at higher frequencies. The X-band device was driven by a short-pulse, 110A, 185 keV electron beam with the orbital-to-axial velocity ratio of 1.2. A saturated gain of 37 dB was obtained over a 21% bandwidth centered on 9.4 GHz frequency. The output peak power was 1.1 MW. The efficiency was close to 30% in spite of the fact that the orbital velocity spread was close to 15%. (Note that from publication...
it is not clear whether the authors mean the RMS spread value.) These results clearly demonstrate the potential of this new concept.

12.3 High-Gain Gyro-TWTs

As we discussed in Chapter 6 (Sec. 6.3), in principle, the gain of the gyro-TWT can be increased proportionally to the interaction length. However, in real devices, the lengthening of the interaction space makes the amplifier operation unstable due to parasitic self-excitation. In Sec. 6.3 we discussed a possibility to avoid this excitation by developing multistage gyro-TWTs in which each stage is short enough for providing stable amplification. We also mentioned there another way to stabilize the gyro-TWT operation, based on the use of lossy materials in an input part of the waveguide. This method, known in linear-beam TWTs, was successfully used in the gyro-TWT experiments carried out at the National Tsing Hua University, Taiwan (Chu et al. 1999). Since in these experiments the highest gain (up to 70 dB) has been demonstrated, we will discuss these experiments below in more detail.

The use of distributed losses as an effective means for stabilizing the gyro-TWT operation with respect to both reflective oscillations caused by the wave reflections from the input/output couplers, and the absolute instability caused by the excitation of backward waves, was proven in previous experiments (Chu et al. 1995). In those experiments a Ka-band gyro-TWT operating at the TE$_{11}$-wave at the fundamental cyclotron resonance was studied. There, the concept of a severed gyro-TWT was tested as well. It was shown that the wall losses distributed over approximately the first half of the waveguide is a much more efficient means to increase the starting current of the parasitic TE$_{21}$-wave—which can be excited as a backward wave at the second cyclotron harmonic—than the use of a sever. These distributed losses produced about a 20 dB circuit loss at the band center frequency. Thus, the wave growth in the lossy section was about 13 dB, while the copper output section added about 20 dB to the gain. So, the overall gain was about 33 dB and the efficiency was about 20%.

A careful theoretical analysis of all kinds of instabilities (Chu et al. 1999) allowed researchers to substantially improve the device performance. In a new set of experiments, the length of the graphite-coated lossy section was increased from less than 10 cm to about 20 cm with a much higher cold circuit loss of about 100 dB. Simultaneously, the length of the conducting wall section was shortened from more than 7 cm to 4 cm. Such a Ka-band gyro-TWT driven by a 100 kV, 3.5 A electron beam with the orbital-to-axial velocity ratio in the range from 0.8 to 1.1 demonstrated an excellent performance with the 70 dB
saturated gain, about 100 kW output power and 26.5% interaction efficiency. Saturated output power over 80 kW with a gain above 65 dB was observed over a bandwidth of 1 GHz. The full-width half-maximum bandwidth was about 3 GHz, which is approximately 8.6% of the center frequency. Note that such an ultra-high gain permits the use of solid-state sources as drivers for high-power amplifiers.

The success of this experiment sparked an interest in this concept at NRL, where presently a similar Ka-band gyro-TWT is under development (Nguyen et al. 2001, Garven et al. 2002). To accommodate high average power operation, in this tube a diffractive loading scheme instead of lossy ceramic will be employed. Nguyen et al. (2001) showed that the peak power/bandwidth characteristics can be significantly altered by changing the electron orbital-to-axial velocity ratio. In experiments (Garven et al. 2002), the peak power of 137 kW was obtained with the 47.0 dB gain, 17% efficiency and 3.3% bandwidth. This device is intended to serve as the transmitter power amplifier in radar systems used for a variety of applications such as precision tracking and high-resolution imaging.

It is worthwhile to mention another experiment that is of great interest to the developers of gyro-TWIs, although it was not focused on the high-gain operation. In that experiment, described by Wang et al. (1995), the tube operated in the TE_{21}-wave excited at the second cyclotron harmonic. This wave seems to be very convenient for the second harmonic operation because, when the beam interacts with this wave at the grazing condition at the second harmonic, there is no intersection of the fundamental resonance cyclotron mode with any wave of a waveguide. This statement was illustrated by Fig. 6.7, reproduced from Wang et al. (1995). The fact that the beam coupling to the waves in the case of interaction at harmonics is smaller than in the case of the fundamental resonance interaction allowed researchers (Wang et al. 1995) to realize stable amplification at the 200 kW output level with an efficiency close to 13%. The measured saturated gain and bandwidth in this Ku-band (16 GHz) gyro-TWT were 16 dB and 2.1%, respectively.