MICROWAVE SOURCES FOR 3-rd AND 4-th GENERATIONS OF ECRIS

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Abstract

Recent results in the development of the electron cyclotron resonance ion sources (ECRIS) have proven the potential of the operating frequency for the production of high-intensity multicharge ion beams. The next ambitious steps are discussed today which include further increase in frequency up to 60 GHz, use of broadband microwave sources, and two- or three-frequency heating. Microwave sources capable of meeting the needs of the next generation of ECRIS are considered here based on many-year experience of the Institute of Applied Physics in the design and fabrication of high-power millimeter-wave equipment and achievements of other research groups. Different varieties of gyro-devices producing broadband radiation (multi-frequency or fast-swept in time) with CW or average power of order of 10-15 kW and the center frequency within the range 24-60 GHz are discussed.

INTRODUCTION

The progress in the development as well as the domain of operating parameters for any microwave power source are strongly stimulated and dictated by the applications. For example, gyrotrons with frequencies of 140 GHz and 170 GHz, and CW power of megawatt level have been developed for thermonuclear fusion installations (tokamaks, stellarators); amplifiers having broad frequency band, pulsed power of order of 100 kW and center frequencies lying in the transparency windows of the atmosphere (e.g. 35 GHz and 94 GHz) were worked out for radars. The electron cyclotron resonance ion sources are a relatively new line of application based on the use of moderate microwave power (on the order 10 kW) at frequencies of tens GHz. A significant improvement of ECRIS performance parameters upon a transition to the frequency of 28 GHz has been prove recently by experimental results obtained at several facilities. According to current concepts, further progress in ECRIS operating characteristics can be achieved using microwave sources of higher frequency and such additional options as fast frequency sweeping (with a sweep time less than 10^{-4} s within a frequency band of few percents) or multi-frequency generation or generation of CW signal with a broadband spectrum [1, 2].

It is generally recognized that the only microwave sources capable of delivering CW or average power on the order of 10 kW in the frequency range of tens GHz are vacuum electron devices based on the cyclotron resonance maser (CRM) instability and using low-relativistic electron beams (particle energy of about tens keV), often called gyro-devices. The operation of these high-power coherent radiation sources (gyro-devices) is based on the interaction of the electrons gyrating in the external magnetic field with a fast electromagnetic wave under the cyclotron resonance condition: $\omega - hv_{\parallel} \approx n\omega_H$, where ω and h are the frequency and the axial wavenumber of the wave, $v_{\parallel}$ and ω_H are the axial velocity and the cyclotron frequency of the electrons, n is the cyclotron harmonic number. The interaction of electrons with fast electromagnetic waves propagating in the cavities and waveguides with smooth metal walls is the distinguishing feature of gyro-devices as opposed to conventional slow-wave electron devices. Since no periodic structure is employed, enhanced power handling capability exists in gyro-devices.

Formally, the orbital bunching of gyrating relativistic electrons has much in common with bunching of linear electron beams being used in ordinary (“O” type) devices. Therefore each CRM has its “O” type analog: monotron, klystron, travelling-wave-tube (TWT), backward-wave oscillator (BWO). The differences in operation principles of these gyro-devices can be seen from the dispersion diagram shown in Fig.°1. This diagram will be discussed later in more detail as applied to each type of gyro-device.

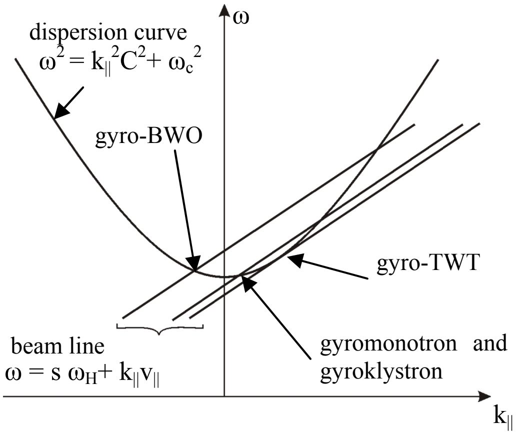

Figure 1: Dispersion diagram showing the operating point for gyro-devices: ω_H – electron cyclotron frequency, ω_c— the cutoff frequency of the waveguide mode, $k_{\parallel}$ – axial wave number, $v_{\parallel}$— axial velocity of electron beam.

A review of the experimental results obtained during last two decades shows that gyro-devices are capable of meeting the requirements imposed by the next generation of ECRIS. Here, the general concepts of various gyro-devices are briefly introduced. Examples of last experimental achievements obtained in application-driven developments are presented to illustrate the feasibility of custom-made gyro-device based systems for ECRIS.

GYROTRON (gyro-MONOTRON)

The feasibility of implementing fixed-frequency gyrotrons for a customer-ordered frequency and power of 10-15 kW in both CW and pulse regimes is beyond question today and gyrotrons operating at frequencies of 28, 37 and 75 GHz are already used in some ECRIS experiments. In the conventional gyrotron the resonant cavity has a fixed structure, and fixed and discreet spectrum of the supported eigenmodes. The gyrotrons operate near the electron cyclotron frequency $\omega_c = eH_0/\gamma m_0$ or its harmonic $n\omega_c$ (e is the electric charge, m_0 is the mass of the electron, $\gamma = 1 + eU/m_0c^2$ is the relativistic mass factor), and the operating frequency can be controlled only by varying the electron beam energy eU (rapid electrical tuning) or the static magnetic field strength H_0 (slow magnetic tuning). Here we omit the case when a resonant cavity of special design has mechanically movable elements such as split walls or inner coaxial rod, since these methods can provide only very slow tuning and, moreover, offer problems with cooling at the CW operation.

As with any kind of oscillators the bandwidth of frequency tuning is inversely proportional to the quality factor of the resonator. For gyrotrons the frequency bandwidth is a function of many operating parameters: $\Delta\omega = (\omega/Q)\cdot F(I, U, H,\ldots)$, where Q is the quality-factor of a resonator, I is the electron beam current, U is the acceleration voltage. The variation of any of the arguments of F leads to a shift of the operating frequency. The qualityfactor in the gyrotrons of moderate power is over 10^3 and the frequency tuning range is typically less than 0.1%. For example, in [3] it was shown experimentally that in the 75 GHz gyrotron with the Q-factor of 10^3 the relative frequency shift at half-power level equaled to 0.1, 0.05, and 0.01% at variation of the magnetic field, anode voltage and beam voltage, respectively. It is necessary to note that any change of the operation parameters changes not only the frequency but also the efficiency of interaction of the electron beam with the electromagnetic wave and eventually the output power of gyrotrons.

Among many research efforts undertaken in an attempt to increase the frequency bandwidth of gyrotrons it is worth noting [4] where a 0.96% tuning range was achieved in an X-band gyrotron with coupled cavities. The RF circuit of the gyrotron consisted of two circular cavities separated by a thin iris. A tenfold increase in the tuning range over that of an ordinary gyrotron resulted from the effective interaction of the electron beam with two modes having the same azimuthal and radial but different axial structures. The frequency tuning was performed by a variation of the magnetic field strength. The efficiency of oscillation was about 18% and remained constant within a ± 1% limit over the whole frequency tuning range.

GYROKLYSTRON

The development of the millimeter-wave K_a-band (34-36 GHz) and W-band (93-95 GHz) gyroklystrons was primarily stimulated by radar applications within the ranges of the atmospheric RF "windows". Later, high-power pulse gyroklystrons attracted attention as sources of coherent radiation for compact, high-gradient linear accelerators. As the result of the radar application-driven efforts, quite impressive parameters were achieved in a K_a-band gyroklystron as early as in 1993 [5]. The two-cavity gyroklystron delivered 750 kW output power in up to 100 microsecond pulses. A maximum efficiency of 32% was obtained at the 300 kW output power level. At the 600 kW power level, the gain was 22 dB and the instantaneous bandwidth at the – 3 dB level was 0.61%. The bandwidth was limited by the Q-factor of the output cavity which was about 320.

The Q-factor of 200-300 is typical for the resonant cavities used in gyroklystrons. The bandwidth of gyroklystrons can be increased by the so-called stagger tuning when the resonant eigenfrequencies of cavities are slightly detuned around the output cavity frequency [6]. This method is widely used in conventional klystrons. In general, the larger is the stagger tuning, the larger both the increase in bandwidth and decrease in gain. However, some reduction of gain is seemingly not very critical for gyroklystrons of moderate power. A high-signal gain of 30 dB is achievable in a multicavity gyroklystron, and a 10 kW output power can be obtained using a solid state driver since an input power of 1 W is sufficient to saturate the device.

Regarding a CW or high average power operation of gyroklystrons, it is necessary to mention the serious technical problem arising from high thermal loads on some components. High-loss ceramic loads are typically introduced between cavities to suppress instabilities and spurious oscillations. Even heavier can be the thermal load in the penultimate cavity of multicavity gyroklystrons.

An example of a successful solution of these problems can be found in [7], where authors reported on the development of a four-cavity W-band gyroklystron delivering over 10 kW average power with 11% duty cycle (100 μs pulse, 1.1 kHz repetition rate). The instantaneous bandwidth of this device at the – 3 dB level was 420 MHz (0,5%), the gain was 35 dB, and the efficiency was 33%.

GYRO–BACKWARD WAVE OSCILLATOR (gyro-BWO)

The gyro-BWO is based on the resonant cyclotron interaction of the electrons gyrating in the external magnetic field with the electromagnetic wave travelling in the direction opposite to the longitudinal velocity of electrons. A gyro-BWO operating with a travelling wave of non-resonant microwave structure can provide broad-band smooth frequency tuning by variation of the magnetic field strength or the electron beam energy.

The gyro-BWO operation has been successfully tested in the early 1990's in a number of experiments. In [8], a short-pulse K_a-band gyro-BWO operating at the fundamental cyclotron harmonic and fundamental TE_{10} mode of a smooth cylindrical waveguide was described. The continuous magnetic field tuning bandwidth was 13% (from 27.5 to 31.5 GHz) and the voltage tuning bandwidth was 3% at the half-power level, while the power approached 7 kW with nearly 20% efficiency. The

3 dB 5% voltage tuning range was achieved in a pulse K_a-band gyro BWO reported in [9].

The relatively low efficiency of backward-wave oscillators is explained by an unfavorable axial structure of the RF field. Electrons are modulated near the entrance to the waveguide structure by a high-amplitude RF field while electron bunches lose the energy near the exit where the field amplitude is low. However, the efficiency can be drastically increased up to 30 and even to 50% by the tapering of the external magnetic field or the waveguide radius, as it was shown in [10, 11].

The use of a novel microwave structure in the form of a helically grooved waveguide was suggested in [12]. A properly chosen helical corrugation of the surface of an oversized circular waveguide provides dispersion of a circularly polarized eigenmode that is favorable for the traveling-wave based gyro-devices, such as gyro-BWO and gyro-TWT. The main advantage of the so produced eigenwave dispersion is in its sufficiently large group velocity at zero axial wavenumber, which ensures broadband operation with minimum negative impact of the electron velocity spread. In the experiments on the helical-waveguide gyro-TWT performed at IAP, the gyro-BWO operation was also studied [13], which was simplified by the fact that switching between TWT and BWO operation required just the change of polarity of the external magnetic field. In these proof-of-principle experiments, stable and reliable K_a-band pulse gyro-BWO operation at the second cyclotron harmonic was obtained. Later, a CW gyro-BWO with a helically grooved waveguide was designed for a number of technological applications [14]. The device operated with a weakly relativistic (20 keV) electron beam. A maximum power of 7 kW with the efficiency of 15% at a frequency of 24.7 GHz was achieved. The frequency tuning range at the half-power level was about 5% when varying the magnetic field (Fig. 2) and 0.8% when varying the beam voltage. The variations in the output power can be explained by reflection from unmatched output window.

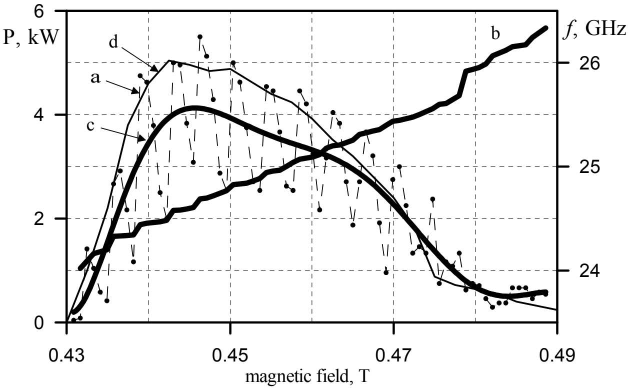

Figure 2: The output microwave power (a) and frequency (b) of the gyro-BWO as functions of magnetic field for the beam voltage of 20 kV and beam current of 2 A; curves (c) and (d) are the averaged experimental output power and the power obtained as the result of the performance simulation, respectively.

A 2.5 kW CW 24 GHz gyro-BWO of a similar design has been incorporated in a two-frequency gyro-device based system for microwave processing of materials, produced by IAP for the Far Infrared Center, Fukui University, Japan (Fig. 3). Another microwave source in this system was a 15 kW CW 28 GHz gyrotron.

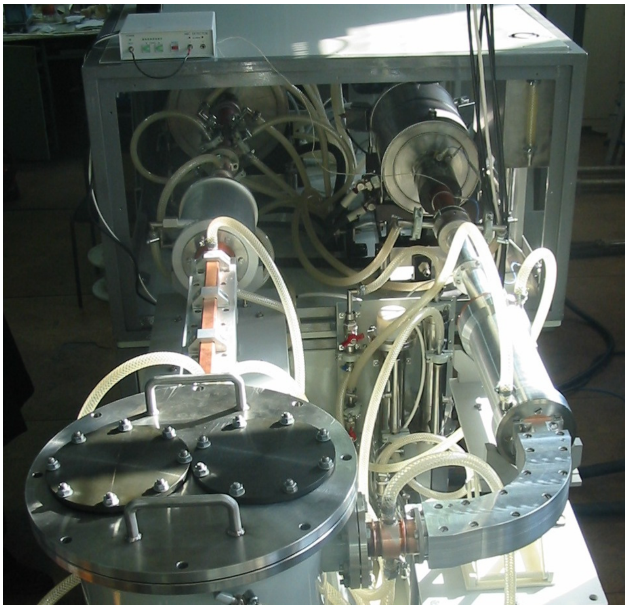

Figure 3: Two-frequency gyro-device based system combined of a 2.5 kW CW 24 GHz gyro-BWO and 15 kW CW 28 GHz gyrotron.

GYRO–TRAWELLING WAVE TUBE (gyro-TWT)

Despite a long history of the development of gyro-TWTs and impressive results achieved by many groups, at present there are no systems in which these devices are used. As is often the case, there is a trade-off between the performance characteristics of a gyro-TWT such as a gain and a frequency bandwidth. This trade-off can be resolved in favor of one or other parameters depending on a given application. Since the next generation of ECRISs needs a rather moderate, for gyro-devices, level of millimeter-wave power it appears that an increased bandwidth is a more critical parameter than a large gain in this application.

At the early stage of research most experiments were performed on pulse gyro-TWTs. The bandwidth exceeding 10% even in the large-signal regime of a K_a-band gyro-TWT was obtained in one of the first experimental works reported in 1990 [15]. Later on, a significant increase in the instantaneous bandwidth up to 33%, the largest for a gyro-TWT, was achieved in a gyro-TWT with the tapered magnetic field [16]. This device operated with the efficiency of about 10% and a small-signal gain in excess of 20 dB.

The implementation of an amplifier operating with high average or CW power is impeded by serious difficulties. The most severe of them is spurious oscillations which arise partly due to the electron velocity spread. The common method for suppression of spurious oscillation is the use of a distributed loss. Most distributed loss stabilized gyro-TWTs to date employ a thin lossy coating that is not compatible with high-average power operation. An elaborate suppression technique was developed at the Naval Research Laboratory, based on loading the most part of the interaction space of a 35 GHz TE_{01} mode gyro-TWT with a lining of lossy ceramic cylindrical shells periodically interspaced with narrow metal rings. A high gain of 60 dB and a 3 dB bandwidth of 4.2 GHz (12%) were achieved but the device was tested in the pulse regime only with a pulse length of 11 μs and repetition rate of 3 Hz [17].

The above mentioned idea about the use of a helically grooved waveguide works advantageously for a high average power gyro-TWT. Low sensitivity of the operation mode to the electron velocity spread allows good stability against oscillations and significant increase in efficiency. In addition, the danger of overheating of the elements of the device is reduced, and proper cooling becomes much easier when a completely metal waveguide structure is used.

The bandwidth capabilities of such a gyro-TWT with a helically grooved waveguide were tested firstly in the X-band (9.4 GHz) [18]. A saturated gain of 37 dB with the efficiency close to 30% was obtained over 21% bandwidth in a short pulse device. Later on, operation of a second-harmonic K_a–band gyro-TWT was demonstrated [19]. A maximum efficiency of 27%, power of 180 kW, saturated gain of 25 dB and instantaneous -3 dB bandwidth of nearly 10% were obtained at pulse operation with a 10 μs pulse duration and a 1 Hz repetition rate.

These results clearly demonstrate the potential of this new concept of the waveguide structure for high average power gyro-TWTs operating in the millimeter-wave range.

CONCLUSION

The experimental results achieved to date demonstrate that gyro-devices of all types considered here can meet the requirements of the next generation of ECRIS in terms of power and frequency. As for the requirements for a frequency bandwidth and frequency sweeping, they can also be met but the detailed specification should be elaborated for each particular facility in order to develop a gyro-device most precisely fitting the user's needs. There is a trade-off between performance characteristics, and the priorities are dictated by a given application.

It is clear that an increase in both the power and frequency of the millimeter wave sources that feed the ECRIS requires a new type of microwave transmission lines. The lines should be composed of the oversized multimode and/or quasioptical components. A large experience in designing such components and transmission lines as a whole has been acquired to date as the result of the development of millimeter wave power facilities for high power applications.

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