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IRREGULAR QUASI-OPTICAL SYSTEMS OF MILLIMETER WAVES ELECTRONICS

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The basic types and research results of irregular quasi-optical systems, applied in electronics and millimeter-wave technology, are presented in the review. The general property of such systems is the presence of inhomogeneities, on which the transformation of surface waves of electron beams (or dielectric waveguides) into bulk waves, exciting the specified type of quasi-optical device (open resonator or waveguide, periodic or dielectric structure and others), occurs. We compared the levels of development for relativistic and non-relativistic electro-vacuum devices. The applicability of construction of low-voltage amplifiers and oscillators of millimeter range, including the planar technology uses for their microminiaturization, is shown. Based on the review we have built the scheme of irregular quasi-optical systems classification and evaluated the most advanced directions for further researches.

Keywords: *IRREGULAR QUASI-OPTICAL SYSTEMS, MILLIMETER-WAVE TECHNOLOGY, SURFACE WAVES, OPEN RESONATOR, WAVEGUIDE*

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1. INTRODUCTION

Electrovacuum devices of millimeter and submillimetric (MSM) waves are widely used in actual problems solving of experimental physics, astronomy, natural resources study, radiolocation, in communication systems, and medicine [1-3]. Increasing requirements to parameters of vacuum-tube oscillators and amplifiers of electromagnetic oscillations have stimulated the search of new structurally-technological solutions and energy conversion mechanisms of electron flux (EF) to electromagnetic field energy. For example, along with the classical devices development of type backward-wave tube (BWT), traveling-wave tube (TWT), magnetron, klystron [4-7] the fundamentally new devices, using radiation effects, such as diffraction radiation generator (DRG), orotron, Cherenkov oscillator, cyclotron-resonance maser, free electron laser [8-14] were proposed and have developed. These effects include the Cherenkov and transition radiations, as well as their varieties: induced radiation, Smith-Parsell radiation (diffraction radiation) [15-18].

The basic aspect of devices, the operating principle of which is based on the application of radiation effects, is the presence of irregular quasi-optical electrodynamic systems, which are realized in the form of open resonators (OR) and open waveguides (OW). Such systems are preferable in the MSM-band due to the formation of bulk electromagnetic waves and high-efficiency selection of oscillations modes.

Open resonators are major elements of a number of MSM-waves devices [19-27]: resonance wavemeters, frequency standards, devices for material properties studying, different modifications of oscillators and amplifiers, including the Gunn semiconductor oscillators and avalanche-diode oscillator (ADO) [28, 29]. Quasi-optical resonance systems found the wide practical application in relativistic electronics as well, for example [1, 30-32]. Trends of using the new modifications of resonance quasi-optical structures in engineering and electronics of MSM-waves are stated in detail in the review [25].

Presently, for electromagnetic oscillations amplification of MSM-waves the using of irregular open waveguides of various modifications, which are excited by the Smith-Parsell radiation, is actively discussed. For the first time such idea for non-relativistic devices was considered in [33]. In the sequel, the physical processes of EF interaction with diffracted on periodic structure field [34] were analyzed; the linear theory of amplifier, which uses the Smith-Parsell effect [35, 36], was developed; the experimental simulation of waves processes in such a system [37] was done; the possibility of energy extraction through dielectric layer, placed between the OW mirrors [38, 39], was considered as well. A common trait of such systems is the presence of OW, containing the distributed radiation source of type “diffraction grating (DG)-electron flux” or “DG-dielectric waveguide”. Here the basic factor for effective amplification of electromagnetic oscillations is the parameters optimization of OW electrodynamic system from the point of view of maximal EF energy conversion to the microwave oscillation energy and its output into load with minimal losses. Metal-dielectric structures (MDS) [25, 40, 41], which allow to implement the modes of the surface waves conversion to the bulk ones using the Cherenkov, the diffraction, and the combination of difraction-Cherenkov radiations, are promising as well as under usage in resonance systems of the OR type. The present modes realization in OW and OR opens up the wide possibilities in enhancement of functional features of devices, based on the Smith-Parsell effect, what is shown in [41-44]. Besides, such systems can be also applied as multifunction devices of the MSM-waves technology under their excitation by diffraction-bounded radiation sources [45].

Appeared during the last years the theoretical and experimental works of applied character [46-48] confirm the prospectivity and actuality of the given scientific field, connected with the study of wave process physics in irregular quasi-optical electrodynamic systems with distributed radiation sources. However the absence of system approach for investigation of above-listed objects complicates their practical realization.

The aim of the present review is analysis of design features and electrodynamic properties of the resonance-waveguide irregular quasi-optical MSM-waves systems, their classification, and thereupon determination of unsolved by now problems of the wave process physics and practical realization in particular circuits of electronics devices and MSM-waves technology.

On the basis of assigned task in the present review the main types of “classical” irregular quasi-optical systems, which found application both in relativistic and non-relativistic electronics of MSM-waves, are analyzed. New modifications of such systems, which were recently proposed and implemented, are considered, and on this basis the general classification scheme of analyzed objects, permitting to determine the paths of their further development, is composed.

2. DISTRIBUTED RADIATION SOURCES OF BULK WAVES

In the MSM-waves electronics for quasi-optical systems excitation the radiation effects, appeared under charged particles motion, are basically used. Cherenkov and transition radiations, and their varieties such as induced radiation, the Smith-Parsell one (diffraction radiation) [8, 11, 15-18, 50-52] are concerning to such effects.

Cherenkov radiation (ChR) becomes excited under the uniform electrons (or other charged particle) motion in a medium with velocity υ_e, bigger than the light speed in this medium. There is the dependence of the phase light velocity υ_{ph} in infinite medium versus the dielectric ε and magnetic μ relative permeabilities, which is defined by relation $\upsilon_{ph} = c/(\varepsilon\mu)^{1/2}$, where c is the light speed in a free space. This electromagnetic radiation is characterized by specific angular distribution, which consists in that the wave vector of radiated waves subtends with the velocity vector υ_e the angle γ_0, assignable by the relation $\cos\gamma_0 = c/\upsilon_e(\varepsilon\mu)^{1/2}$. Since $\cos\gamma_0$ is always less than unity, the ChR is possible only at $\upsilon_e > \upsilon_{ph}$. The ChR is also observed in the case if electron moves not only in continuous medium, but the distance about radiated wavelength [15] off the medium. However, proposed in initial step of vacuum electronics development circuits of the Cherenkov oscillators [53] did not receive future development due to lack of dielectrics then, which have large values of ε and low losses on high frequencies. Such dielectrics appearance as polycor, rutile, and $BaLn_2Ti_4O_{12}$-, $BaCe_2Ti_4O_{12}$-, $CaZnO_3$ - $CaTiO_3$-based alloys [54] has stimulated the ChR study under its excitation in dielectric medium by relativistic [55-57] and non-relativistic [11, 58, 59] electron fluxes.

In the case of ChR it is supposed that medium, in which this radiation arises, is uniform and its properties are time-constant. If medium properties vary with time along the trajectory of particle motion, then radiation arises at any velocity of charge motion [60]. Such radiation was termed as the transition one. In the simplest case transition radiation occurs on the interface of two mediums under straight-line and uniform charge motion with any velocity, and found wide application in diagnostic of electron fluxes microstructure [61, 62].

If particle moves nearby other inhomogeneities such as screens with holes or finite bodies, the radiation arises as well, and it is termed as the diffraction radiation (DR) [8, 17]. The physical nature of the transition and diffraction radiations is the same. Field of transiting particle induces in inhomogeneity the alternating currents or charges. Moving charge and inhomogeneity represent two necessary components for radiation arising. With periodic location of inhomogeneities the intensity and coherence of diffraction radiation are essentially increase [8, 11].

It is shown in [11] that properties of the DR zero harmonic are identical to the ChR ones in a medium. In addition, DR has a number of features, proper only this radiative phenomenon: radiation in vacuum is possible only on the negative harmonics; there is the energy transfer from one radiating harmonic into another, that is the Wood's anomalies take place; amplitude of DR harmonic decreases with its number increasing.

For the first time electron-wave mechanism of DR excitation by relativistic EF, which interacts with diffracted on the periodic structure field, was studied in [63] and in the sequel was termed as Smith-Parsell effect. The substance of this effect is in the following: during transmission of focused by electric and magnetic fields relativistic EF nearby the plane optical reflecting DG with certain period the positive feedback is carried out by own DG waves, which provide phasing under interaction of considerable number of electrons on minimal distances off the lattice. As a result the coherent radiation of optical range, spreading under different angles, is observed.

For non-relativistic EF the electron-wave mechanism of DR initiation for the first time was studied in [64-66] and generalized in [11]. Shown, that in real diffraction electronics devices the EF, which excites DR, represents complex active system, described in linear approximation as a superposition of longitudinal and transverse current waves set, spreading with different phase velocities. Such EF structural changes lead to splitting effects of radiation directivity diagrams, changes of polarization characteristics of excited field, and spurious DR. Additional aspects of radiation excitation physics are considered in [67], where the theory of Smith-Parsell effect of unmodulated EF subject to double-mode radiation is developed, and spatial distributions of time harmonics amplitudes of radio-frequency current are determined as well in low-signal self-consistent consideration.

Besides the charged particles fluxes (relativistic and non-relativistic) as distributed sources of bulk waves formation (radiation model) in electronics and MSM-waves technology the dielectric waveguides (DW) are found wide application as well, which during their location along the periodic inhomogeneities of different types allow, due to the surface wave presence, to simulate the excitation conditions of Cherenkov and diffraction radiations in irregular quasi-optical systems [37, 41]. DG - DW combination allows to solve questions of complex antenna systems formation [21, 22] and energy extraction in electronics devices [38, 39].

3. RESONANCE QUASI-OPTICAL SYSTEMS

Hemispherical OR with periodical inhomogeneities of reflecting DG type (see Fig. 1) are found wide spread occurrence in MSM-waves electronics. Such electrodynamic system is used in orotrons and DRG [8, 11].

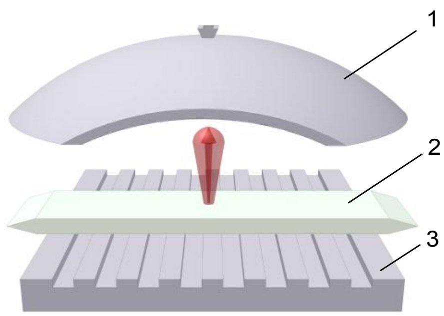


Fig. 1 *– Hemispherical OR with diffraction grating: 1 – spherical mirror with energy extraction; 2 – distributed radiation source (DG or DW); 3 – plane mirror with reflecting grating*

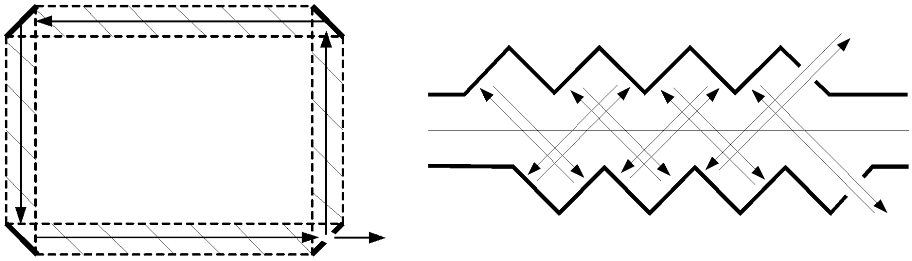
DRG operating principle is based on the effect of diffraction radiation, which is excited by EF, moving nearby DG, located in OR [11, 14, 68-73]. In this case, interacting with diffracted on grating incident field, the regimes of amplification and electromagnetic oscillations generation are implemented. So, DRG output characteristics are appreciably defined by properties of used OR. The presence of periodical structure in DRG OR essentially modifies the electrodynamic characteristics of classical resonance quasi-optical structures. During the plane mirror production in the form of reflecting grating (the orotron model) [69-73] the overall losses are considerably increase, and as a result the Q-factor for such a system becomes four times less. Q-factor reduction occurs due to incidental losses, which appear during power leakage for waveguide waves radiation, spreading in channels to mirror edges, where the reflection coefficient is not equal unit.

Therefore for such systems the hemispherical OR, only the central part of which is covered by diffraction grating [8, 11, 68], was proposed. Such resonator has more rarefied vibration spectrum, in which radiation losses depend on geometrical grating parameters. Changing the grating width it is possible to change not only a number of oscillations types, exciting in OR, but to govern the distances, where the higher-order oscillations can occur. Losses in OR essentially depend on relation between the grating period and the wavelength, on which resonator becomes excited. Changing the depth of reflecting grating channels the maximal Q-factor of oscillations can vary several times. In hemispherical OR with local DG the TEM_{20q} oscillation type is basic. Cited in [8, 11] investigation results showed that in such a system the perturbation due to DG is insignificant, if minimum in field distribution is situated above the interface between grating and mirror. This occurs at DG width larger or equal than the main lobe width of TEM_{20q} oscillation field.

During semiconductor sources and MSM-waves elemental base realization the angled-echelette OR are found wide application as well. On the basis of such electrodynamic systems in [74, 75] the modifications of quasi-optical solid-state pumping oscillators with sphere-angled-echelette OR, which structurally implemented by schemes with reaction-reflecting and transmission resonators, are proposed. As it is shown in [28, 29] the vibrating system of angled-echelette OR has a number of features: the spectrum sparseness degree of such OR spectrum is a little bit less than of OR spectrum with plane echelette mirror. However there are oscillation types in spectrum with anomalously high Q-factor, qualified as quasi-fundamental oscillation types. The field of quasi-fundamental oscillation types is tightened to the OR axis, and their energy density is bigger than for fundamental and other types of oscillations. Nearby the angled-echelette mirror a field structure undergoes transformation, and nearby the peak of OR it is closed to field structure in rectangular waveguide. Angled-echelette mirror is a many-stage impedance transformer.

Variety of relativistic electronics devices, for example, [1, 9, 56, 76], conditioned the necessity of development of special open resonance electro-dynamic systems, possessing by heightened electric ruggedness and effective selection of oscillation types. To such resonance systems, particularly, one can ascribe the ring resonator, represented a set of mirrors, which are located by the following way: the beam, reflected from resonator mirrors, is closed up with optical beams splitting of direct and reflected signals (see Fig. 2a).

Inherently, in resonator volume the mode of progressing waves is implemented. Besides, no less than two supplementary optical branches appear, through which the other devices can switch on. This feature was used in one modification of free electron laser with cascade frequency growth [77]. In the MSM-range the Bragg resonators using (see Fig. 2b) is challenging as well. Structurally they consist of Fabry-Perot resonators, which mirrors form sawtooth or wavy image surfaces. Such resonators are basically used in free electron lasers designs [12, 77, 78]. Be notable for the multi-functionality the Bragg resonator is a multifrequency system. Besides, for pumping wave, spreading along the resonator axis, the set of mirrors is a highly selective slowing structure.



a b

Fig. 2 *– Schemes of quasi-optical resonance systems of relativistic electronics devices: ring resonator (a), Bragg resonator (b)*

In [11, 79-83] the diffraction electronics devices based on coupled OR are proposed and partially explored, which in comparison with single-cavity DRG possess a number of advantages: they have more wide range of electronic frequency tuning, can be effectively used as oscillators, power amplifiers, and frequency multipliers. In such devices an OR coupling can be implemented either through diffracted on the mirrors edges field [11, 80, 82] by serial arrangement of oscillators, or through diffracted on the band gratings field [83, 84] by parallel connection of oscillators relative to the axis of a distributed radiation source.

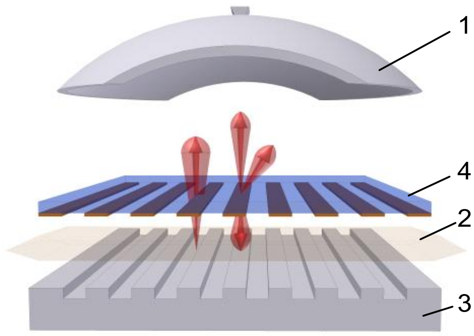


Fig. 3 *– Resonance quasi-optical system with MDS: 1 – spherical mirror; 2 – distributed radiation source; 3 – reflecting grating; 4 – periodic MDS*

During the last years the application of OR with MDS, which allow to implement different regimes of energy transformation of the surface waves to the bulk ones by changing parameters of their electrodynamic systems

[25, 85-89], in MSM-waves electronics is actively discussed. The example of such a device is represented in Fig. 3.

Between OR mirrors there is a MDS, fulfilled in the form of dielectric layer, on which a band DG is deposited. Such electrodynamic system is basic under formation of diffraction-Cherenkov oscillators. However, during its using it is necessary to take into account all possible excitation modes of diffraction-Cherenkov radiation (DChR) by distributed radiation source, located close to the interface between the dielectric layer and the band DG. Experimental results of wave simulation physics of DChR for spatially bounded MDS are partly analyzed in [90]. It is shown in [41, 91, 92] that MDS introduction into open resonator can lead to the qualitatively new electrodynamic properties of such a system: changing MDS parameters the realization of energy attenuation modes in OR, the oscillations amplitude and their Q-factor increasing, and the oscillation selection are possible. Further study of such systems [49, 93-96] allowed to propose and validate the specific dia-grams of diffraction electronics devices with spatially-developed resonance structures: the diffraction-Cherenkov oscillator, the Cherenkov BWT.

4. WAVE PROPAGATION QUASI-OPTICAL SYSTEMS

Wave-propagating quasi-optical systems found the widest application in relativistic electronics, where they are used as channeled or localized elements of electromagnetic waves energy. Generally they are irregular or weekly irregular waveguides. To their variety one can ascribe super-dimensional waveguides of different forms and sections, waveguides with periodic inhomogeneities such as conductive helical of the “comb” type, pin waveguides, Bragg and diaphragmatic waveguides, different types of dielectric waveguides.

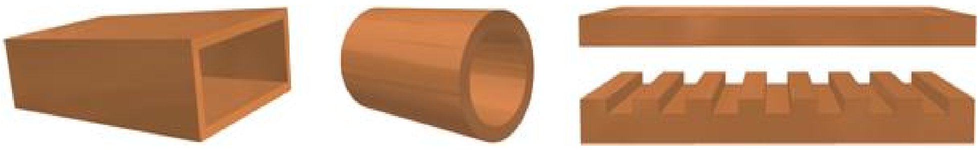
Application of superdimensional waveguides is determined by requirements of systems electric strength in the presence of high powers and radiation effects using for electromagnetic oscillations generation. Thus, for example, in the Cherenkov oscillator [97] the waveguide system with diameter-to-wavelength ratio, which is equal to 13, is used. Usually this ratio in different relativistic oscillators makes 5-8 [9].

Together with the microwave-energy input-output function from an interaction volume of EF and electromagnetic wave in some relativistic devices the open irregular waveguides are used as devices, providing an effective energy exchange between EF and electromagnetic wave. For example, the waveguide lines of slow waves or slowing structures are the primary elements of relativistic devices, such as free electron laser (FEL), relativistic DRG, TWT, orotrons, and Cherenkov oscillators. In other words, slowing structures can perform the function of EF modulation, provide phase-focusing condition execution, and promote the energy extraction from EF within the fulfillment of electron over-population condition in stopping phase of electromagnetic field. In this case periodic structures are selective devices, determining the properties of waves, which are propagated over them, that essentially defines the interaction mechanisms of EF and electromagnetic waves, and the radiation input-output modes from devices as well.

Besides, the periodic slowing structures are the electromagnetic signals transducers in active mixers of electromagnetic waves of millimeter and submillimetric range, and are the surface waves transformers to the bulk ones and inversely as well. Periodic metal structures found an application in FEL – dopletrons with microwave pumping by slow electromagnetic wave [77], in relativistic TWT [9, 98], in Cherenkov oscillators [13, 97], in relativistic DRG, and orotrons [9]. During FEL pumping (E-ubitron) wiggler bifilar superconductive spiral [77] is applied, the analog of which is used in the classical TWT. In [12] the using of Bragg grating of planar geometry additionally gives wide possibilities for radiation input-output from the FEL-amplifier.

Except the metal irregular waveguides, the dielectric slowing systems are used, which can also combine in itself the energy input-output functions and participate in the conversion of EF kinetic energy to electromagnetic field energy. For example, in [13, 55] the Cherenkov microwave-amplifier with slowing system in the form of circular waveguide with dielectric rod is investigated. The convenience of such a system consists in ability of radiation output into free space without alternate routes and waves transducers. Note, that there are two structurally different types of Cherenkov oscillators and amplifiers. In the first type a dielectric medium, above which relativistic EF (Cherenkov radiation) moves, is used as radiation source. In the second one an EF and periodic structure (diffraction radiation) are radiation sources.

The basic types of open waveguide systems, applied in relativistic electronics, are represented in Fig. 4.



a b c

Fig. 4 *– Basic types of open waveguide systems, applied in relativistic electronics: rectangular waveguide (a), circular waveguide (b), slowing structure (c)*

For solving the problem of broadband amplification of MSM-band electromagnetic waves the waveguide irregular systems find application in non-relativistic vacuum electronics as well. Presently the simplest amplifier of millimeter range is implemented on the base of DRG, operating in pre-transition regime of oscillations excitation, that is at beam currents less than the starting one [99]. In such device the bandwidth of gain signal is defined by OR Q-factor, and at the best, is equal to resonator passband. For the first time the waveguide type of Smith-Parsell amplifier was proposed in [33]: the non-relativistic EF 1 interacts with progressing bulk wave of diffraction radiation in an open waveguide system, formed by the surfaces of passive 2 and active 3 (with diffraction grating) mirrors (see Fig. 5).

The questions of amplification possibility of electromagnetic waves in a system, represented in Fig. 5b, where an open waveguide is formed by the surfaces of passive 2 and active 3 mirrors, fulfilled in the form of reflecting gratings, were considered in the sequel. The band EF 1 moves along the active mirror 3 surface. Close to the surface of passive mirror 2 there is the dielectric waveguide 4 with the energy input-output units. Under quasi-synchronism of EF velocity the electron grouping into beams, radiating at the input signal frequency, occurs from one of the surface waves. On the passive mirror grating there is backward transformation of the bulk wave to the surface one of dielectric waveguide with its following reradiation into OW. Subject to in-phase radiation from the active and passive mirrors the amplification effect of the OW forward wave by the slow wave of EF space charge is observed.

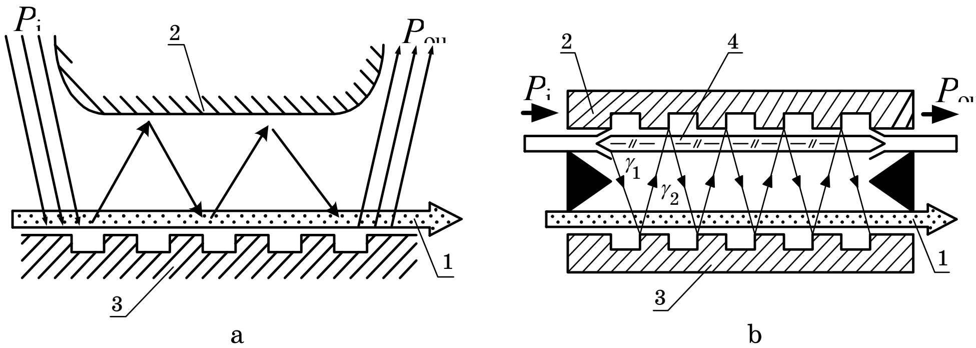


Fig. 5 *– Diagrams of non-relativistic amplifiers based on an open irregular waveguide systems: amplifier [33] (a), amplifier [34, 100] (b)*

An OW system with dielectric layer, located in the area of passive mirror 2 (see Fig. 5a), is promising from the point of view of quasi-optical output realization of electromagnetic waves energy. For such a system the linear self-consistent theory of electromagnetic waves amplification on the Smith-Parsell effect is developed and takes into account the influence of dielectric layer and EF thickness on the conditions of oscillations excitation in OW [38, 39, 101-106]. It is established that varying the electrodynamic parameters of OW the realization of different conditions of system excitation is possible, such as the DR mode along the normal (regenerative mode), the bulk traveling-wave mode, and the surface wave mode (BWT, TWT).

In the case of amplifier integral version the planar periodic MDS is of practical interest as well, that in the simplest case is formed by metal shield and dielectric layer, on the lateral surface of which the band diffraction grating is applied [41, 107]. Along grating there is a distributed radiation source, which subject to system parameters can excite different space harmonics with numbers $n = 0, \pm 1, \pm 2,...$ and energy density S_n [11, 41]. For such a system the numerical and experimental simulation methods of different DChR excitation modes [40, 108-111] have developed, which allow to define the proportions of energy density of space radiation harmonics and optimize parameters of electrodynamic system according to the assigned task.

5. CONCLUSIONS

Based on the done review in Fig. 6 we represent the classification of irregular quasi-optical systems of different modifications, used in electronics and MSM-waves technology, which allows to illustrate their variety and single out the class of structures, for which the optimization problems of electrodynamic characteristics are not solved up to now.

Resonance and waveguide quasi-optical systems of different modifications form the basis of relativistic and non-relativistic MSM-waves devices. Resonance and waveguide systems of relativistic devices, providing electromagnetic oscillations with high energies [1, 9], are the most studied theoretically and experimentally by now. The distinctive feature of such electrodynamic systems are electrical and mechanical strengths to the thermal action of electromagnetic field; the support of interaction maximum between the fields and relativistic flux; the increased functionality of oscillating system, providing the simultaneous efficiency of EF interaction with the field and input or output of microwave oscillations.

The necessity of realization of above-mentioned principles in non-relativistic devices leaded to formation of a new class of quasi-optical irregular resonance systems, the base of which are the hemispherical OR and DG of different modifications: reflecting DG, band DG, angled-echelette DG and OR with periodic MDS. The distinctive feature of such devices is using of EF of mean energies, which do not need the special support of increased electrical and mechanical strengths to the thermal action. The properties of these electrodynamic systems are sufficiently fully studied and used in non-relativistic electronics and MSM-wave technology [11, 21, 25].

At present, the irregular waveguide quasi-optical systems of non-relativistic devices are less examined, on the base of which different modifications of Smith-Parsell amplifier [38, 39] are proposed.

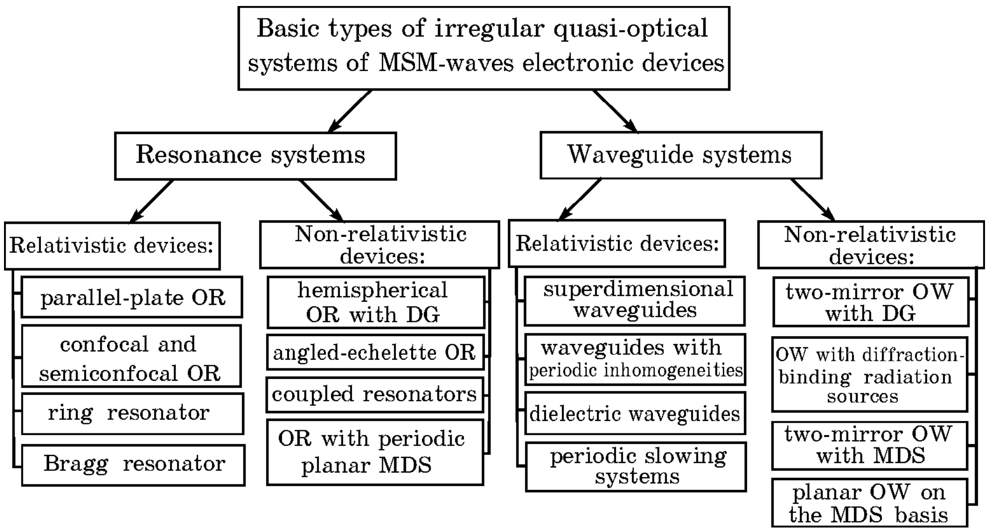


Fig. 6 *– Classification of irregular quasi-optical systems, used in electronics and MSM-wave technology*

The simplest system, which is sufficiently fully studied (both theoretically and experimentally), is the two-mirror OW with DG, along which the EF moves (see Fig. 5). For such amplifier modification with parallel-plate mirrors the one-dimensional linear self-consistent theory is developed, which does not take into account the magnetic focusing field influence on the electron-wave processes, and the experimental simulation of wave properties of electrodynamic system is carried out. An influence of mirrors phase correction on formation of progressing wave along the OW axis is partially considered. OW with diffraction-bounded sources of waves excitation, which are the basis of amplifier production, according to the diagram of Fig. 5b, and an element base of MSM-waves [48], are studied on the level of experimental simulation [45]. We defined the general regularities of wave processes physics in OW with periodic MDS, which can also be used as independent elements under construction of planar systems of MSM-waves devices [112].

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