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THE EXPERIMENTAL PLANT AND MODELING METHOD FOR SPATIAL WAVES IN MULTICOUPLED QUASI-OPTICAL SYSTEMS WITH PERIODIC INHOMOGENEITIES

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The experimental plant and the general method of modeling of electromagnetic wave processes in multicoupled quasi-optical systems are described. Examples of choosing the optimum regimes of modeling and basic parameters of the investigated electrodynamic systems are shown. The functional scheme of the experimental plant is also described. The general method of modeling of electromagnetic phenomena in resonant and wave-guide multicoupled quasi-optical systems is presented for the first time.

Keywords: *WAVE, DIFFRACTION GRATING, DIELECTRIC WAVEGUIDE, METAL-DIELECTRIC STRUCTURE, OPEN RESONATOR, ELECTROMAGNETIC RADIATION.*

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1. INTRODUCTION

At present, multicoupled quasi-optical systems (MQS) find wide application in both electronics and microwave engineering [1-4]. The basic principles of the excitation of electromagnetic oscillations in such systems are based on the transformation of surface waves of dielectric waveguide (DW) or space-charge waves of electron flow (EF) into bulk waves of diffraction radiation (DR) on periodic inhomogeneities located in the bulk of an open resonator (OR) or open waveguide (OW).

Modern theoretical methods of electromagnetic field modeling do not allow to solve definitely the problems of optimization of the MQS electrodynamic parameters from the point of view of their practical realization. In connection with this, the preference (with respect to the immediacy of receiving information and the reliability of the results) is given to the experimental methods, some of which are expounded in works [5-8], concerning the certain objects of the investigation. Therefore, development of these methods in terms of the expansion of the class of problems, which can be solved by experimental modeling of the wave processes in complex MQS, is very promising.

In the present work, the general approach to the experimental modeling of the electromagnetic phenomena in complex multicoupled quasi-optical systems with periodic inhomogeneities is proposed and realized for the first time.

2. GENERAL PRINCIPLES OF THE WAVE MODELING AND EXPERIMENTAL PLANT CONSTRUCTION

General principles of the wave modeling are based on the analogy of properties of the plane nonuniform wave of the proper field of monochromatic EF with the surface wave of DW, which are stated in detail and grounded in [9]. The construction and realization technique of such a model in the experiment consists in the following:

1. Determination of the basic requirements for the experimental facility: measuring equipment should provide the transformation of surface waves into bulk ones; measurement of the radiation angles of spatial harmonics in the sector from 0 to 180° with the absolute error, which does not exceed 1°; control of the wavelength and power propagating in DW.

2. Choice of the optimal coupling of the diffraction grating (DG) fields with DW surface wave, which is characterized by the minimum distortion in the spectrum of the spatial harmonics of DR at their maximum intensity.

3. Determination of the radiation power level. Radiation power is the most important characteristic during the transformation of surface waves into bulk ones and is concentrated in the directional lobes. To measure this power, two methods can be used. The first method consists in the measurement of the directional radiation patterns. The second one is based on the measurement of the DW waveguide characteristics, namely, the standing wave ratios (SWR) and the wave transmission coefficients into the matched load or power meter.

3. CHOICE OF THE SPATIAL WAVE SIMULATION MODES

The above described principles of the wave modeling are based on the example of the use of a reflection metal DG, which has limited functional capabilities as to the realization of the DR properties, which can also appear on periodic metal-dielectric structures (MDS) [5]. Since MQS contain coupling elements in the form of complex two-row metal and metal-dielectric DG, under their investigation the main question is the choice of simulation modes of wave processes corresponding to the given type of quasi-optical system, namely, to the OR or the OW with the bulk wave emitter. In connection with this, we consider the general case of DR excitation on periodic MDS, assuming that metal DG in some approximation are the particular case of radiation system with dielectric layer at $\varepsilon = 1$.

It follows from the general solution of the problems of DR wave modeling [5, 9] that the transformation channel of DW waves into bulk ones, which is conditioned by violation of total internal reflection in DW, is the model of Cherenkov radiation. Such channel is realized if dielectric permeability $\varepsilon_{в}$ of the waveguide does not exceed ε of the medium, and phase velocity of wave propagation in DW satisfies the condition of the Cherenkov radiation excitation. Channels of leaky waves from DW into dielectric medium or simultaneously into vacuum and dielectric are the model of EF DR. On the basis of identification of the EF and DW surface waves [10], and, respectively, the relative velocities of electrons β_e and waves β_w in DW, the general conditions of radiation of electromagnetic oscillations into vacuum (1) and dielectric (2) have the following form:

$$\frac{\kappa}{|n| + \kappa} \le \frac{\beta_w}{\beta_e} \le \frac{\kappa}{|n| - \kappa}, \tag{1}$$

$$\frac{\kappa}{|n| + \kappa\sqrt{\varepsilon}} \le \frac{\beta_w}{\beta_e} \le \frac{\kappa}{|n| - \kappa\sqrt{\varepsilon}}, \tag{2}$$

where $\kappa = l/\lambda$; l is the lattice spacing; λ is the radiation wavelength.

Starting from (1) and (2), the radiation angles of electromagnetic waves into vacuum γ_{nv} and dielectric $\gamma_{n\varepsilon}$ for the specified parameters β_w and β_e are determined by the relations:

$$\beta_w \to \gamma_{nv} = \arccos\left(\sqrt{\varepsilon_в} + \frac{n}{\kappa}\right), \; \gamma_{n\varepsilon} = -\arccos\frac{\sqrt{\varepsilon_в} + \frac{n}{\kappa}}{\sqrt{\varepsilon}}, \tag{3}$$

$$\beta_e \to \gamma_{nv} = \arccos\left(\frac{1}{\beta_e} + \frac{n}{\kappa}\right), \; \gamma_{n\varepsilon} = -\arccos\frac{\frac{1}{\beta_e} + \frac{n}{\kappa}}{\sqrt{\varepsilon}}. \tag{4}$$

As follows from the analysis of relations (1) and (2), for the parameters κ, β_e (β_w) and ε only negative spatial harmonics with $n = -1, -2, -3,$... are excited in a free space, and harmonics with $n = 0, \pm 1, \pm 2,$ ... – in dielectric medium. Radiation on the zero ($n = 0$) spatial harmonic occurs at the electron velocities $\varepsilon\beta_e^2 > 1$ with the radiation angle $\cos\gamma_{0\varepsilon} = 1/(\beta_e\varepsilon^{0,5})$. Therefore, such radiation can be called as the Cherenkov radiation (ChR), and grating can be considered as a shielding factor, which influences the coupling coefficient of EF or DW with dielectric medium [11].

The above described radiation modes can be visually analyzed by the construction of the Brillouin diagrams using the technique stated in [5] for the specified values of the dielectric permeability. Taking into account the fact that currently there is a sufficient variety of materials with low microwave loss, which can be used in both the experimental modeling (small values of ε – teflon, polystyrene, polycor) and production of low-voltage vibration sources using MDS (large values of ε – ceramics based on the barium and titanium oxides [12]). As an example, in Fig. 1 we present the basic fragments of the diagrams for vacuum ($\varepsilon = 1$) and the most widespread in the microwave band materials ($\varepsilon = 2$-150) in the coordinates κ and $\eta = \kappa/\beta$.

It is seen from the comparative analysis of the Brillouin diagrams that with the deposition of the ribbon DG on the dielectric layer surface, electrodynamic properties of the system change considerably in comparison with the metal grating in a vacuum due to the appearance of new transformation channels of DW-EF surface waves that is illustrated in Fig. 1b-d.

In connection with this, we designate the discrete areas on the Brillouin diagram by the numerals N_s^m ($N = 1$-5), which determine the most typical cases of the excitation of electromagnetic waves by the EF (surface wave of DW). The lower indexes $s = 0, \pm 1, \pm 2,$ ... indicate the numbers of spatial harmonics, which are radiated into dielectric, the upper indexes $m = -1, -2,$ ... mean radiation into vacuum. Thus, for example, area 1_0 corresponds to the excitation of the fundamental Cherenkov harmonic; area 2 – to the surface waves; area 3 – to the DR into dielectric medium only; areas 4, 5 are characterized by the possibility of the excitation of DR harmonics into both free space and dielectric medium.

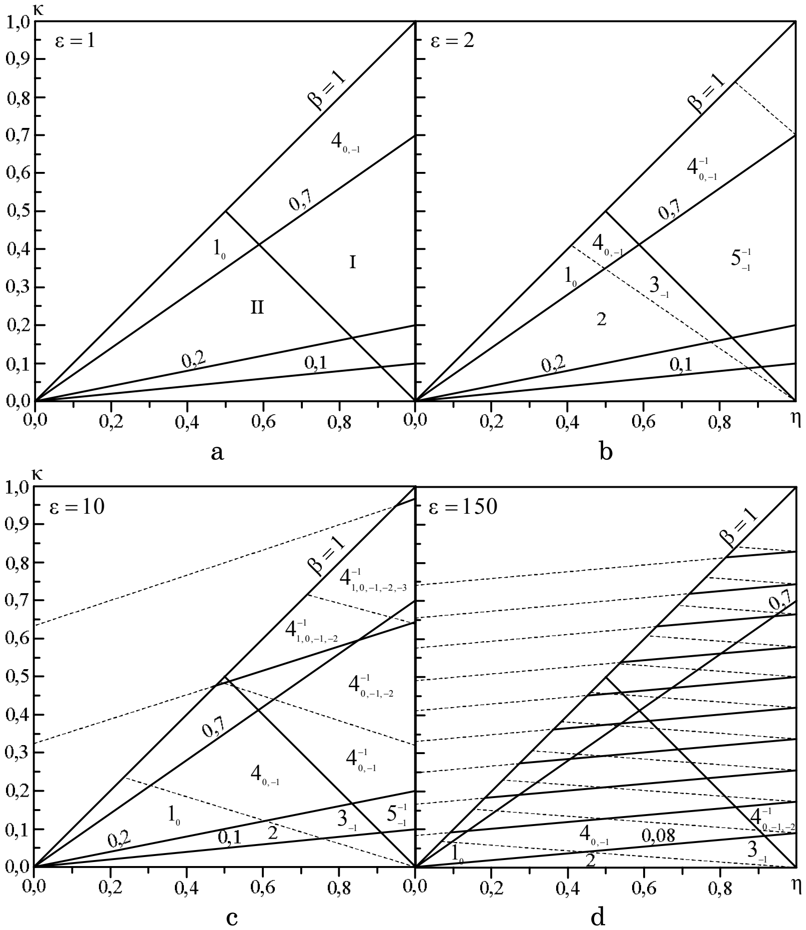

Fig. 1 – Brillouin diagrams at the excitation of spatial waves on metal gratings (a) and MDS (b-d) for different values of ε

As seen from Fig. 1, with the increase in ε, a number of Brillouin zones increases at constant κ, and areas of the intervals over parameters κ and β, where they are excited, decrease. In particular, realization of both the ChR and diffraction-Cherenkov radiation (DChR) modes is possible in the region of non-relativistic EF for the values $\varepsilon \geq 100$ (Fig. 1d). From the point of view of the production of low-voltage radiation sources, 3_{-1} zone is of practical interest, where DR, similarly to the ChR, appears only in dielectric of MDS, but at sufficiently lower electron velocities. Taking into account the specificity of the conditions of the bulk wave excitation of such mode, we will conditionally call it the anomalous diffraction radiation (ADR) [13]. To realize the low-voltage devices of the type of diffraction radiation generator (DRG) (for example, orotron), the radiation mode in 5_{-1}^{-1} zone at the lattice parameters, which provide radiation along the normal with respect to the OR mirrors, is of practical interest.

4. FUNCTIONAL DIAGRAM OF THE EXPERIMENTAL PLANT AND DESTINATION OF ITS MAIN UNITS

In [5, 6] there were described the installation diagrams for the investigation of the transformation of DW surface waves into bulk ones on the MDS of semi-infinite thickness and on metal periodic structures, which allow to solve only particular questions of the wave modeling without regard to the specificity of the studied MQS, namely, the possibility of the presence of spatial waves in both the coupling area and out of it in the volumes of OR and OW; influence of the dielectric layer thickness on the radiation characteristics in MDS; necessity of the automated control of the main parameters of the waveguide transmission line; accounting of the radiation loss into ambient space.

As follows from the above stated general principles of the wave modeling, converter of DW (EF) surface waves into bulk electromagnetic ones is one of the main units of the experimental plant. Converter can be realized for MQS in different modifications: ribbon and reflection DG, periodic MDS and their different combinations (for example, double DG, DG-MDS, etc.). DW, which forms the surface (exciting) wave, is the key element here. It is supplied from the source of microwave oscillations and is the main waveguide element in MQS, through which the SWR and the transmission coefficients of electrodynamic system are controlled.

Starting from the foregoing, in Fig. 2 we present a universal functional diagram for the measurement of the electrodynamic characteristics of MQS, which can be modified for the concrete objects of investigation by the minor changes.

As it was mentioned, system of coupling and spatial wave excitation I is the main functional unit of the plant. It is part of the studied object II and in Fig. 2 it is conventionally shown as DW 1 and periodic inhomogeneities 2. DW 1 through the matching transitions 3 is connected to the measuring unit of the waveguide characteristics III and to the control-matching unit of the output power IV. Field registration systems V, VI in far and near radiation zones, signals from which are registered by the plotter P, are the peripheral units of the diagram presented in Fig. 2, as well as the general mechanical system of angular and three-dimensional adjustment of the elements VII of the studied object.

System of coupling and spatial wave excitation I can be realized in different modifications. Radiated waves are the source of electromagnetic oscillations in quasi-optical structures like OR and OW, whose elements, in turn, influence the radiation source due to the return of bulk waves to the coupling area from the reflecting apertures that will appear in the change of the integral waveguide characteristics of DW. Therefore, at the realization of the diagram in Fig. 2, units III and IV, which allow to control the SWR and the transmission coefficients K_T of MQS, are one of the main units.

Measuring unit of the waveguide characteristics III represented in Fig. 2 is constructed based on standard panoramic meter of the voltage standing-wave ratio (VSWR) and attenuations, which consists of the sweep-frequency generator (SFG) connected with indicator of VSWR and attenuation through the system of automatic power regulator (APR), directional couplers 4, 5 with detector sections plugged in with the corresponding connectors of the VSWR indicator. APR is used to provide the constant power level at the input to the studied object. Depending on the way of coupler connection with the measuring line, we have determined either SWR (scheme of the coupler connection in Fig. 2) or transmission coefficients.

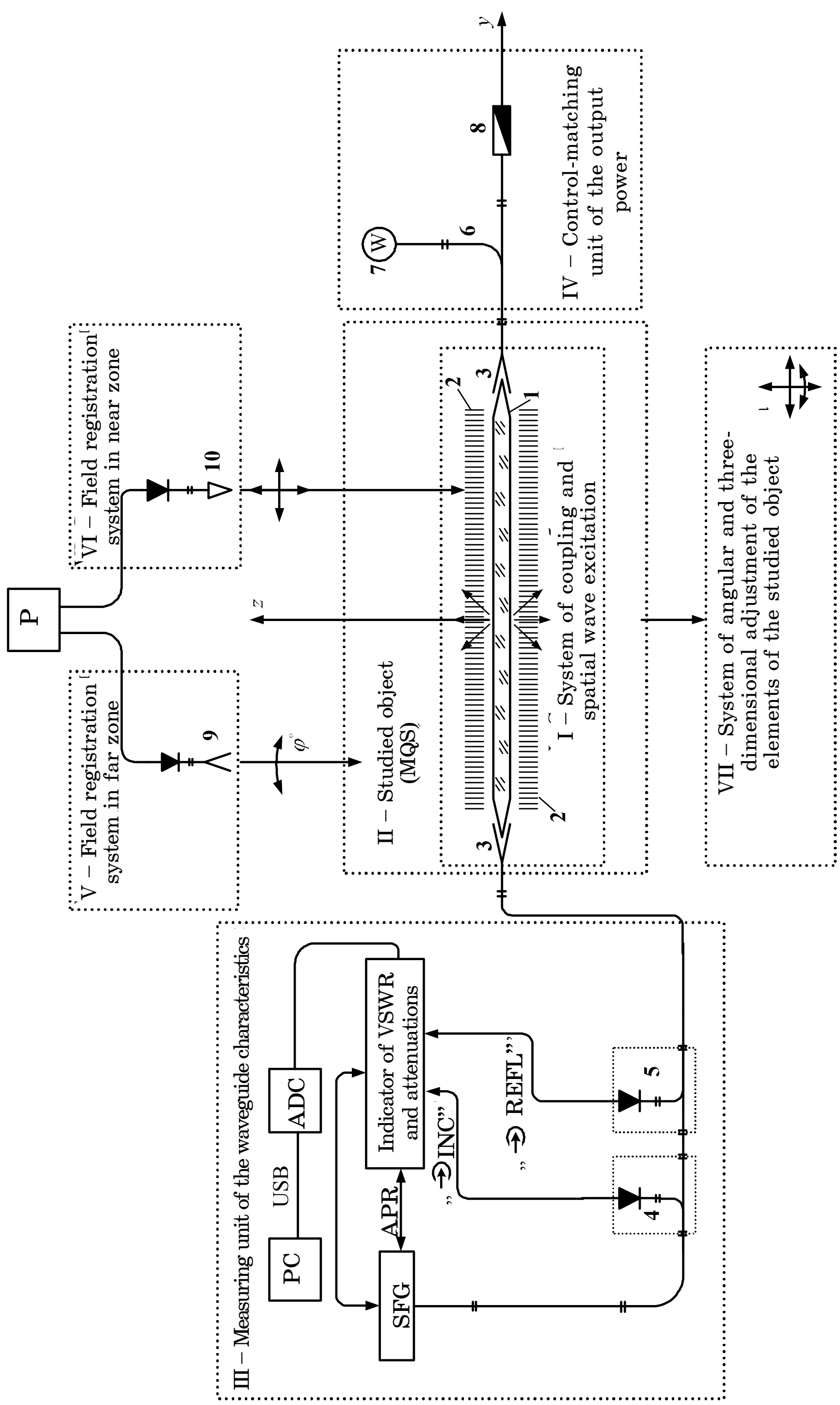

Fig. 2 – *Functional diagram of the electrodynamic characteristic measuring of MQS*

Treatment of the obtained data was performed by a specially developed analog-to-digital converter (ADC) with the interface USB, using which the measuring data was transferred to the personal computer (PC) for further processing. Feature of the data acquisition and processing was the following: the data arrived at the PC synchronously and at equal time intervals (0,5 s) that allowed to fix the results of the waveguide characteristic measurement with high precision.

Control-matching unit of the output power IV consisted of the directional coupler 6, the bolometric or thermistor power meter 7 (which was plugged in to the direct arm of the coupler 6), and the matched load 8 (which was plugged in to the main duct of the coupler 6) providing small values of SWR in transmitting duct of the plant. While measuring values of K_T, coupler 5 was plugged in to the main duct before coupler 6 that allowed to realize the automatic control of the ratios of the incident and the transmitted into load 8 powers.

Field registration system in far zone V consisted of the mobile horn antenna 9 with detector section, whose rotation axis in the E-plane passes through a radiating aperture and coincides with the vertical axis of the studied radiating structure z, and rotation axis in the H-plane coincides with the DW longitudinal axis 1 y. This provides registration of the radiation angles in the range $\varphi = 10\text{-}170°$ with the accuracy $\Delta\varphi = \pm\ 0{,}5°$. Installation of the mobile part of the field registration system is realized on a special precision mobile device allowing to install the horn antenna in far zone of the studied fields, which is determined by the known relation $z \geq a_m^2/\lambda$, where a_m is the maximum size of the antenna aperture.

While measuring the directional radiation pattern (DRP), a signal received by the horn after detection passed to the input “Y” of 2D plotter P, whose input “X” was plugged in to the sensor of the rotation angle of the receiving horn. Thus, during movement of the mobile antenna, the DRP is fixed on P. After transformation of this DRP to the digital form, it is used for the electronic data processing.

Experimental investigation of the fields in near zone is necessary because the transformation of surface waves into bulk ones occurs in the region of DW-DG system. Field registration unit VI in near zone ($z \approx \lambda$) contains the small sounder 10 (Fig. 2) in the form of dielectric wedge ($\varepsilon = 2{,}05$), which is conjugated with the standard metal waveguide via the matching transition. The surface field indication system was placed on the carriage providing the accuracy of reading over x, y, z coordinates of the order of 0,05 mm. To perform the measurements, it is necessary to set the distance $z \approx \lambda$ between the sounder and the studied object and switch on the sounder movement system along the y-axis. A signal from sounder after detection passed to the P input with further electronic data processing. Amplitude field distributions along the x-axis were carried out similarly. The characteristic size of the sounder was $0{,}1\text{-}0{,}2\lambda$ that provided minimal field distortions in the measurements.

Mounting and adjustment system of the studied object elements VII represents a general bed, on which the uprights and holders of the waveguide ducts (depending on the assigned tasks, arrangement of one or two ducts are possible) are placed and fastened (and if necessary, can move), as well as the adjusters, on which the studied objects (gratings, mirrors, etc.) are fastened. Adjusters were developed and constructed in IRE NASU. They represent a system of mutually perpendicular platforms, which allow to direct and move gratings and mirrors of OR and OW along the x, y, z axes using micrometer screws providing a measurement precision of ± 0,01 mm along the coordinate axes and possibility of the angular correction of $\Delta\varphi \approx 0,1°$.

The described functional diagram was realized in the frequency range of f = 30-80 GHz by using three kits of standard measuring and waveguide equipment of the millimeter wave band.

5. GENERAL MODELING TECHNIQUE OF ELECTROMAGNETIC PHENOMENA IN MULTICOUPLED QUASI-OPTICAL SYSTEMS

Based on the functional capabilities of the represented in Fig. 2 diagram, a general modeling technique of electromagnetic fields in MQS was developed. It consists in the following steps.

1. Implementation of calibration of the main measuring elements of the microwave duct using techniques [14] and DW used in the experiment.

Calibration of DW consists in the determination of the relative velocity of the surface wave on the frequency ($\beta_в = F(f)$) for waveguides with different cross-sections (or with the same cross-section) made of different materials. For these purposes, we used the reflection DG in the form of rectangular bars, whose parameters are calculated from the condition of radiation at the central frequency at an angle of γ_n = 90°, which is defined by the formula

$$\gamma_n = \arccos(1/\beta_в + n/\kappa). \quad (5)$$

Calibration of DW consists of some stages:

- matching of DW with the waveguide duct; in this case reflection DG 2 is removed from the interaction zone with the surface wave ($a > \lambda$), and by optimization of the parameters of matching transitions 3 the values of SWR = 1,1-1,2 for the specified frequency band are achieved;
- obtaining of the one-lobe directional pattern at an angle of γ_{-1} = 90° by approaching of DG to the DW surface on the distance of $a \le \lambda$;
- determination of the radiation angles of directional pattern subject to the frequency;
- calculation of the values of $\beta_в$ on the frequency by the formula (5);
- construction of the calibration characteristics of DW.

As an example, in Table 1 we present the main parameters of the calibrated DW for the specified frequency range, and in Fig. 3 we show their characteristics. For other frequency subranges, calibration of DW is identified for the object with the given parameters κ, $\beta_в$ and ε.

Table 1 – Parameters of the dielectric waveguides used in the experiment

Waveguide number	Cross-section, mm	Material
№1	3,4 × 1,9	teflon
№2	5,2 × 2,6	teflon
№3	5,8 × 3,1	teflon
№4	5,2 × 2,6	viniplast
№5	7,2 × 3,4	polystyrene
№6	7,2 × 3,4	viniplast

From the comparison of the calibration characteristics (see Fig. 3) follows that DW of teflon (№1, №2) and polystyrene (№5) have the lowest frequency dependence. This fact should be taken into account during the experiments with respect to the field modeling in the radiating MQS.

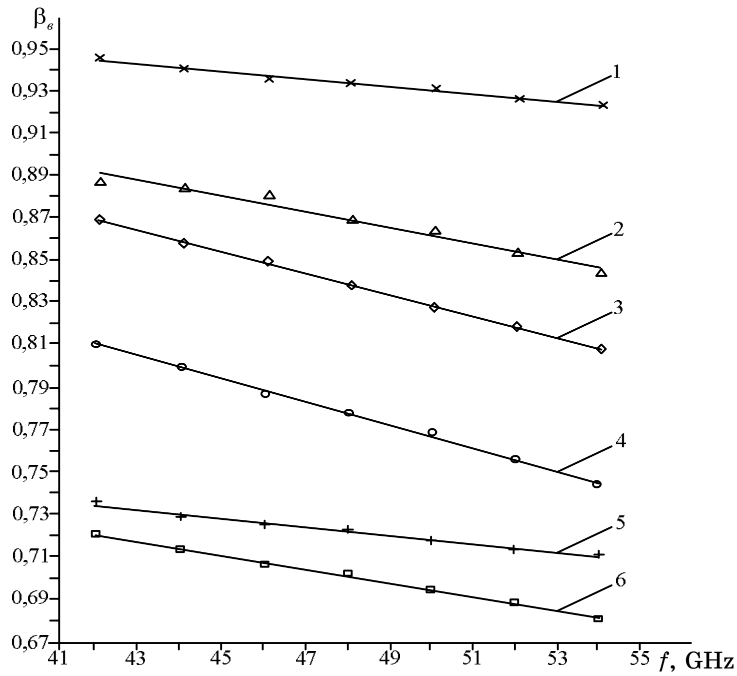

***Fig. 3** – Calibration characteristics of DW (used in the experiment) for the specified frequency range*

2. Determination of the optimal impact parameter *a* for the given DW type.

Optimal value of *a* is determined by the minimum distortions in the lobes of directional pattern at maximum values of their amplitudes on the central frequency of the studied band.

3. Determination of the parameters of the given periodic inhomogeneities of the coupling area and DW.

The optimal parameter domains of periodic structures and DW are determined for the specified radiation modes of spatial waves using the Brillouin diagrams (Fig. 1), and the radiation angles are calculated by the formulas (3) and (4).

4. Measurement of the spatial characteristics of the coupling area (in far and near zones) with simultaneous automatic control of their waveguide characteristics.

During the given cycle of measurements for the specified configuration of the coupling system, the diagram of Fig. 2 is used.

5. Measurement of the electrodynamic characteristics of MQS of the given modifications (OR, OW) with the following electronic processing and analysis of the obtained results.

The above described technique is general for both the resonant and waveguide systems. However, depending on the specificity of the studied MQS, it can be defined more precisely and expanded by peripheral diagrams of measurements, for example, while determining the spectrums and quality of OR by the field registration systems through the coupling elements in mirrors.

6. CONCLUSIONS

1. General principles of the spatial wave modeling in MQS, which are based on the identification of EF and DW surface fields, are formulated.
2. Universal experimental plant of the millimeter wave band, which allows to realize the electromagnetic phenomena modeling for a wide class of MQS (two-row DG, periodic MDS, multicoupled OR, OW) is developed.
3. General technique of the electromagnetic phenomena modeling in MQS is developed. This technique consists in the following:
   - implementation of calibration of the main measuring elements of the microwave duct, as well as DW used in the experiment;
   - determination of the optimal value of the impact parameter a for the given type of DW;
   - calculation of the parameters of the given periodic inhomogeneities of the coupling area and DW;
   - measurement of the spatial characteristics of the coupling area (in far and near zones) with simultaneous automatic control of their wave-guide characteristics;
   - measurement of the electrodynamic characteristics of MQS of the given modifications (OR, OW) with the following electronic processing and analysis of the obtained results.
4. Developed scheme of the experimental plant and general modeling technique are applicable for all types of MQS that is especially important when investigating the electromagnetic fields in the objects, whose rigorous mathematical description is absent.

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