ELECTRODLESS MICROWAVE DISCHARGES AS SOURCES OF LIGHT AND UV-EMISSION FOR THE ILLUMINATION AND BIOMEDICAL APPLICATIONS

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Abstract, The report contains some results of the researches and designings of Microwave-light modules for the Illuminating and Irradiating plants, which use the electrodless Microwave discharges in (he different gases. The main problems and their solutions are considered for use in the plants of quasi-Sunlight and ultraviolet (UV) irradiation. The phenomenologica! picture of discharge excitation and stabilization is presented. The irradiation spectrums are shown. Some results and features of the creation the bactericidal plant for the complex Microwave, UV- and ozone treatment are presented.

1. INTRODUCTION

In 1992 experts of Fusion System Corporation (Maryland, USA) designed high efficient source of bright quasi sunlight radiation — electrodless microwave gas discharge sulfur tube. The spherical electrodless Argon-Mercury UV lamps with excitation by microwave energy in the frequency band 915-2450 MHz were prototypes of such device.

Main difference of the sulfur lamp from prototype is use of working medium (sulfur instead of mercury) which the power electrodless microwave discharge takes place,

High-power light radiation of the sulfur lamp is characterized with continuous (molecular) spectrum close to sunlight spectrum, but with reduced UV and IR radiation levels.

In October 1994 Fusion Lighting Inc (FL) company demonstrated in Washington two effective illumination systems - outdoor illumination of the DOE Headquarter (US Department of Energy) and indoor illumination system in the large hall of the National museum of aeronautics and space (NASA). These "presentations" attracted attention of experts-designers and perspective consumers to a new light source which introduction was accepted as the most considerable technological breakthrough in development illumination technology on the border of XXI century.

The first illumination systems on the base of sulfur tube used microwave excitation of power 3-4 kW (from two magnetrons of 1.7 kW), the illuminated light flux more than 400 klm and were characterized with the total output light efficiency not more than 75 lm/W. The highest results achieved in 1996 with the best power light device were: illumination flux of 480 klm, output light efficiency 95 lm/W. However, at that time there was no mass production of such power light systems so we have not informed on mass production of such systems up to nowadays.

In 1996 FL company manufactured an analog of Solar 1000™ system (with light flux 138-140 klm at microwave power 800-1000 W), and by 1998 this company in cooperation with Sweden company IKL (Celsius Group) created prototypes of Light Drive 1000™ with the similar output parameters. The last light device has monoblock design that provides its use as autonomous light source so as light source for a hollow light guide.

The first prototypes of working microwave light devices in Russia (in Headlight projector design) were created in Russia in 1996 Open Stock Company "Pluton" in cooperation with VEI and some other enterprises. Some modifications were manufactured as for headlight projector applications so for lighl guide systems (designed by "Svetoch-PRO" and "Svetoch-SV" enterprises). Universal Russian demonstration monoblock model which is similar to devices Solar 1000™ and Light Drive 1000™ at first was demonstraled at the International exhibition "Interlight-98" in Moscow (December 1998) and won the first place in the nomination "Energosaving". At present time our works on development and modification of microwave light sources are being run ("Sveton" from "VET" and "Pluton"). There are data on microwave light sources on the base of sulfur lamps presented in Table 1.

Table I. Distinguishing features of Light devices.

Specifications	Base example	NASM example 1994	Example of 1995/96	Solar-1000™ 1996	Light-Drive 1000™ 1997-98	Svetoch-PRO 1997	Svetoch-SV 1998	Sveton [1] 1999-2000
1	2	-i	4	5	6	7	8	9
Total luminous flux, klm	410	445	480	135	135-140	135	135	135
Microwave power. kW	3,4	3,1	3,1	1,0	1,0	0,9	0,9	0,9
Input power, kVA	6,3	5,9	5,1	1,375-1,425	1,4	<1,325	1,325	1,325
Total lighting efficiency, Im/VA	-65	-75	94	91.5-98	98-100	-102	102	102
Correlated color temperature	6500	6300	-6000	-6000	-6000	-6000	-6000	-6000
Color rendering index	86	86	86	-79	78-79	78	78	78
Starting time, s	5	5	5-15	15-25	15-25	10-15	10-15	10-15
Cooling condition	Forced air with rotating lamp			Conventional with rotating lamp				
Reflector aperture	Round for light-guide "3M" 0254 mm				a) round for light-guide 0254mm b) round 0400mm c) rectangular	a) round for light-guide 0254mm b) round 0350mm for projector	round for light-guide 0254 mm	a) round for light-guide 0254mm b) round for asymmetrical and symmetrical rereflectors

Continuous of Table I.

1	2	3	4	5	
Advantages	• spectrum close to sunlight • very low level of UV and IR • Small lighting body and uniform of illumination • No environment hazards				
	high level of luminous flux short starting time		high lighting efficiency application of high quality magnetrons		
			possibility of lighting drive	high stability of magnetron work low level of the fifth harmonic	
			light mono-block		monoblock moveable
Disadvantages	high level of acoustic noise difficulties with microwave leakage		long time (about 5 min) for repeat starting		

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[1]"VEI"and"PLUTON"

If in illumination installations the energy of microwave oscillation is used only for pumping of an electrodless lamp, the combined irradiation installation developed in Russia (Microwave-Ultraviolet-Ozone) provide not only microwave pumping but also direct effect on irradiated object.
The results of experimental researches have shown considerable amplification of bactericidal effect of such installation in compaction with only microwave or ultra-violet radiation or ozone treatment effect. It is possible to use the some modifications of bactericidal installation as domestic polyfunctional Microwave Oven.

2. MECHANISM AND FEATURES OF WORK

Physical mechanism of work of foreign made and domestic made sulfur lamps consists of photons radiation with multiple transitions of energy states of evaporated sulfur molecules excited or ionized by microwave discharge in a small volume limited with a spherical quartz envelope.
Each transition has substructure due to rotational and vibrational substructures superimposed on each electronic state. Most probable optical radiation is in the UV-region, but because the optical depth of plasma "body" is large enough, the almost all radiation from bulb is in visible diapason and has continuum light emission due to the broadening of vibrational and rotating lines by high pressure and temperature of the working mixture of gas and vapoure. Only during the "start up" phase of microwave discharge, when the sulfur vapoure pressure is small, yet the UV-emission from the lamp is large enough, but this phenomena has a very short time, which depends on the microwave power input into lamp (or, more correct, on the intensity of electrical microwave field and its distribution). If the UV-emission is desired, for example, as bactericidal irradiation factor (λ=253.7 nm), the envelope fill material may be argon (starting gas) and mercury. In this case the visible light is the "by-product", and irradiation spectrum is of continuum, but has a typical lines. The emission on the line λ=180 nm make up the ozone in the surrounding air or oxygen.
The process of transformation of microwave energy (energy of pumping) in optical radiation (OR) is characterized by phenomenon sequence. After magnetron switching-on, as soon as amplitude of microwave field electrical component in a resonator (in a zone of a Sulfur lamp arrangement) reaches an appropriate potential of ignition, a microwave discharge arises in a buffer gas mixture (argon) and saturated vapor of sulfur which is while in a solid condition. At this stage rather lamp radiates a separate lines spectrum corresponding to typical energy transitions in atoms of argon and sulfur. With it there arc rather noticeable levels of ultraviolet (UV) and infrared (IR) components presented in an optical radiation spectrum.
In a process of microwave energy absorption by low pressure discharge and growth of number of ionization acts, the concentration of charges in plasma grows, bombardment activity of envelope surface (coated with precipitated sulfur due to previous switching-on -off and cooling of a lamp) increases mainly for the account of the most mobile carriers of a charge - electrons. As a result of bombardment (mainly in a direction

of microwave electric field force lines) envelope temperature grows fast, and sulfur vapor partial pressure grows also. This process passes a melting stage of different polymorphic sulfur modes (112,8^{0}C; 119,3°C), and then full evaporation stage (boiling temperature: Tboil = 444,6°C), when concentration of sulfur molecules in an envelope becomes rather high. In a stable plasma mode (in the high pressure discharge) the resulting optical radiation (OR) spectrum has a "molecular" character stipulated, as is marked above, plurality of energy condition, including rotating and oscillating conditions of molecules. Spectrum becomes continuous, and typical lines (including lines in UV and IR areas) are merged in this spectrum, though due to heating of an envelope in a continuous optical radiation IR- "wing" appears more elevated in comparison with the UV band. This feature of a spectrum is saved at a different levels of microwave energy pumping and at various initial amounts of sulfur in a lamp of the given size, though with other equal conditions common "displacement" of a continuous spectrum in "far blue" or "red" area can be controlled at the expense of initial amount of sulfur, and also at the expense of introduction of those or other "additives" in a working substance. If selenium is added as such "additive", a feature of stationary plasma mode process is that selenium has higher melting temperature (221°C) and boiling temperature (685,3°C) and, accordingly condensation temperature after deenergizing a microwave pumping. Therefore at different stages of plasma mode and envelope temperature the partial pressure of a vapor-gas mixture of argon, sulfur and selenium vary unequally, that finds its reflection in a character of optical radiation spectrum in transient and stationary modes.

In argon-mercury UV-lamps a phenomenon picture of stationary microwave discharge is more simple, as far already at room temperature a partial pressure of saturated mercury vapor in a mixture with argon is rather large.

If low pressure discharge is used, the mercury is not completely evaporated (working temperature - 60 - 70°C). Radiation spectrum remains with typical resonance lines of argon and mercury, and in an LJV-range (λ= 283,7 nm, λ = 185 nm) optical radiation is the most high.

3. MAIN DIRECTIONS OF WORK ON USE ELECTRODELESS MICROWAVE-DISCHARGE SOURCES OF OPTICAE RADIATION FOR LIGHTING AND IRRADIATING SYSTEMS (DEVICES).

Depending on purpose of a system, such parts can be included into its structure as the main functional elements: a light-transparent microwave resonator or microwave screen, a former of an optical radiation flux (reflector) or an irradiation working chamber, which in its turn can execute functions of a microwave resonator, including non-transparent one. During work of such system microwave energy is partially absorbed by plasma and is transformed into optical radiation (useful effect), is partially reflected to a pumping microwave generator, rendering influence on the output power P_{out}, on the frequency of generated oscillations f_{gen} ("pumping frequency"), and on operational mode. Besides, some part of microwave energy is radiated in ambient space. If as useful "product" it is necessary to receive just optical radiation, for example - for illumination or UV irradiation, microwave energy radiation should be considered as harmful effect requiring suppression up to biologically safe level.

Recently we have created irradiation installations, which both such "instruments": optical radiation in UV band and microwave radiation are used for deliberate effect on alive and lifeless objects completely are used. In this combination microwave energy alongside with a realization of pumping function is also independent " useful product".

It is possible to speak today about forming three rather independent directions in construction lighting (illuminating) and irradiating devices, installations and systems.

1'lrst from these directions covers construction of autonomous lighting fixtures and UV-irradiators, for example, of projector type, with the specific form of optical radiation flux and its spectral distribution. The second - construction of light sources, combined (integrated) with one or multi-channel light-distribution system on the base of light-guides.

The third - construction of complex systems of UV + microwave radiation for various objects and mediums. There are general problems in all these directions of a basic essence character, and some specific features. At present it is possible to make their integrated grouping.

So, let us group main problems in appropriate blocks, that more or less visually problems, facing to the developers "were highlighted".

a) Problems relating to a lamp (torch).

There are the following problems in this block of problems:

- Choice and optimization of structure, quantitative parameters and frequency of filling media, responsible for start forming and stationary maintaining of microwave discharge, for character of optical radiation spectrum and it preservation during operation time.
- Choice of the envelope form, its sizes, material and processing technology, providing of required symmetry and accuracy of manufacturing of each copy and recurrence from a copy to a copy in production line.
- Determination and providing necessary temperature and its distribution on envelope surface in stationary operation mode and in cooling mode after deenergizing.

b) Problems relating to the microwave pumping system.

There are the following problems in this block:

- Choice of power level and form of microwave signal (continuous, amplitude-modulated).
- Creation of systems for "transportation" of microwave energy from a source (magnetron) to a load (electrodlcss lamp) and devices assigning (depending on oscillations mode) a topography of microwave field in space of its interaction with the lamp working substance (in its initial condition and in plasma mode).
- Providing (maintenance) stability of microwave generator (magnetron) work on a load essentially varying during development of microwave discharge (during time interval from start up to reaching stationary plasma mode).
- The prevention of an inadvertent microwave radiation in an environment at pumping frequency f_w (in ca.se if optical radiation is the only '"useful product") and harmonic frequencies ($2f_{vv}$ ...$5f_w$ ...nf_w) etc. collateral oscillations, accordingly, in maintenance of ecological safety and electromagnetic compatibility (EMI), with it an accompanying complex problem is determination of the compromise between light-transparency and microwave resonator walls microwave-opasity, while interaction of microwave fields with plasma torch takes place in the resonator.

c) Problems relating to forming of an optical radiation stream (beam).

There are the following problems in this block:

- Choice form, sizes and reflector (reflectors) material with consideration separations or combining functions of the optical former and microwave resonator.
- Providing design compatibility of reflector with microwave resonator, light-distribution system, with cooling system and lamp rotation device , and in some cases - with irradiated objects (for combined UV-microwave radiators)

d) Problems relating to the power supply system, control and protection of optical radiation source as complex system (device).

There are the following problems in this block:

- Choice and optimization of magnetron power supply voltage form.
- Definition of objects which are being a subject of control and protection, kinds and character of the physical factors, which change the control (protection) system should operate.
- Choice of a kind of the carrier of transmitted information, appropriate sensors and receivers of control signal, converters of this signal in control command and actuators realizing a control operation.

e) Problems relating to the operation process. There are the following problems in this block:

- Providing resistance and stability to external influencing factors (climatic, mechanical) while in service lamps and systems as a whole.
- Providing operation with selected and given combination of different kinds of radiations and additional effects (for example, ozone effect) on irradiated object.

f) Problems relating to the light-distribution system.

The arc in this block, in particular, problems of choice and reali/ation optical radiation delivery means to illuminated or irradiated objects (beam, hollow or fiber light-guides).

g) Problems relating to the philosophy and measurements engineering:
There are the following problems in this block:

- Microwave measurement in a static operation mode ("cold measurements") including measurements parameters of microwave resonator, microwave adapter, microwave exitor and microwave tract in assembly with these elements.
- Microwave measurement in dynamic (transient) operation mode (with working pumping microwave generator and light torch), with evaluation of microwave power level, penetrating through transparent walls of microwave resonator at working frequency, measurement of relative levels of collateral oscillations and harmonics (EMI problem).
- Light and spectral measurements in dynamic (transient) operation modes in conditions complicated by microwave resonator or microwave screen and former of a light beam (flux);
- Thermal measurements including determination of temperature on different points of the light torch envelope surface during starting-up on stable duty of stationary burning, cooling repealed energizing. This

list does not include all complex of problems rising at creation of optical radiation systems, using the electrodless discharge lamps with microwave pumping,

In the field of creation lighting fixtures (illuminators) and illumination systems (within the framework of the first two directions) the achievements of foreign colleagues represented (illustrated) by systems Solar 1000 ™ and Light-Drive 1000 ™ allow to evaluate positively the ways, used by them, some from which confirm and supplement domestic works experience on quasi-sunlight sources (Tabl.l). Speaking on creation irradiation bactericidal installations using electrodless microwave discharge lamps of UV-range (band) and useful in this case microwave effect on completely antiseptical treatmented objects, the desktop installation developed by us and manufactured at the "Pluton" Company demonstrates achievements and engineering solutions in this field. The original devices and operation modes are realized in this system which provide positive results practically in all the listed blocks of problems.

4. SOME EXPERIMENTAL RESULTS. EXAMPLES OF DESIGNS.

The electrodless lamps, light torches with various filling composites, with various dosing and with various technological features of manufacturing were subjected to experimental studies. The interactions of microwave electromagnetic fields with vapor-gas mixtures in lamps of various forms and si/.es in resonators working at various kinds of oscillations (including multi-mode resonators) and, accordingly, having space distributions intrinsic to working operation mode ("topography"), electrical and magnetic components of microwave fields were investigated.

In particular, the resonators and oscillation modes with azimuth-symmetrical field (TEM, TE_{01p}). with azimuth-inhomogeneous field (TE_{11p}) and with superposition fields (TH_{nmp} + TM_{mnp}) were used. With it the features of work (behavior) and "output" parameters of optical radiation of lamps depending on amplitude and form of pumping "signal" were investigated.

There arc some examples of radiation spectrum for sulfur and sulfur-selenium lamps in a stationary operation mode are presented in Fig. 1

It is seen from Fig.l, that the adding selenium in composition of working vapor-gas mixture displaces a spectrum in the "red" band.

The spectrum of sulfur lamp at various microwave pumping power are shown in Fig.2. It is seen from Fig.2, that the change of pumping power almost in 3 times does not result in displacement of cxlremum on wavelength coordinate and changes practically proportionally the radiation flux. There are the spectrums of sulfur lamp in transient regime are presented in Fig.3-7. It is seen, that with the envelope temperature growth and, therefore, with the pressure growth pressure, the reducing of start gas (argon and atomic sulfur) intensity lines takes place. Simultaneously in the "blue-violet" area the "molecular" spectrum is formed. Passing the intermediate conditions, the radiation spectrum is completely "smoothed out" in stationary mode (T_1= 700°C) (Fig.l).

It should be noted that with use an off-standard crystal there arc typical lines of impurities arise on a continuous spectrum (K, Li, Na).

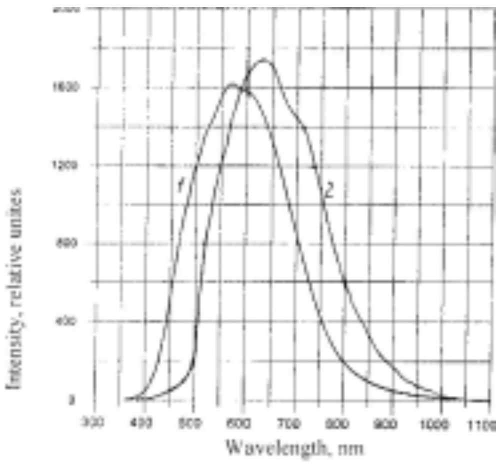

Figure 1. Spectrums of the lamps: 1 - sulfur. 2-.sulfur-selenium. Stationary working conditions.

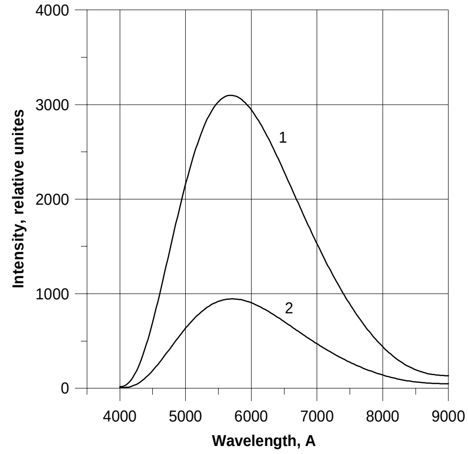

Figure 2. Spectrums of the sulfur lamp at microwave power; I - 1400 W, 2- 560 W.

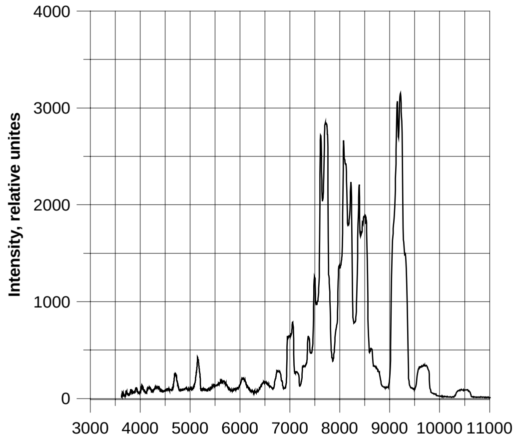

Figure 3. Spectrums of the sulfur lamp at the envelope temperature, T_C=31°C.

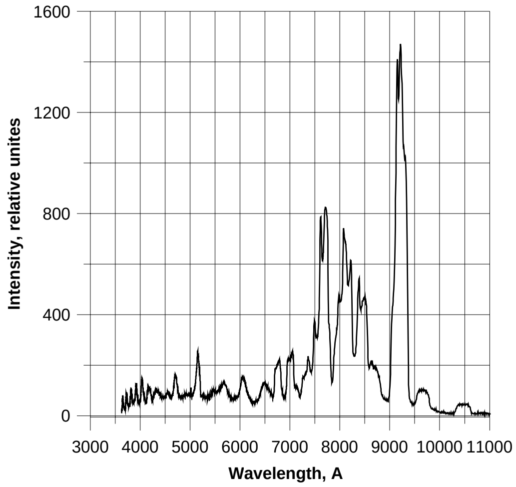

Figure 4. Spectrums of the sulfur lamp at the envelope temperature, T_C=48°C.

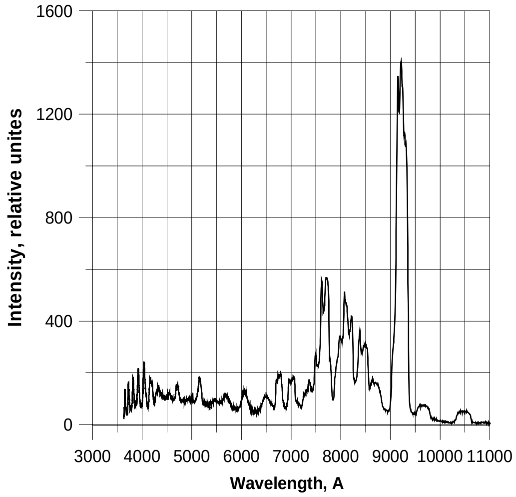

Figure 5. Spectrums of the sulfur lamp at the envelope temperature, T_C=56°C.

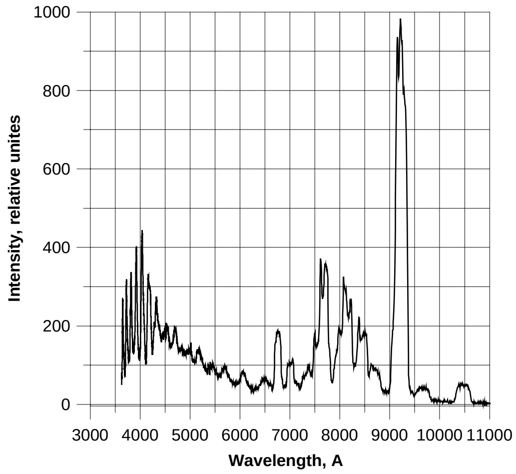

Figure 6. Spectrums of the sulfur lamp at the envelope temperature, T_C=75°C.

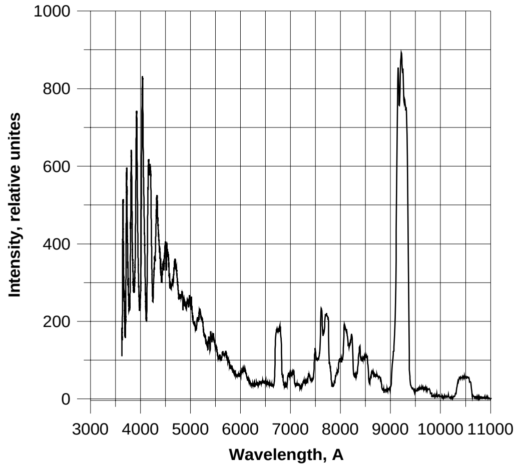

Figure 7. Spectrums of the sulfur lamp at the envelope temperature. T_c=112°C.

In difference from sulfur lamps, intended for the lighting (illumination) purposes, working temperature of mercury electrodlcss lamps intended for combined bactericidal effect (irradiation) (UV-Microwave-Ozone) is in limit up to 70°C (at least with using of the low pressure discharge), that ensures large freedom in choice the form of lamp, cooling method and quality of crystal.

The first modification of the bactericidal installation was designed as the scientific research instrument for the specialists in sphere of biomedical and others new technologies. There are some interchangeable accessories for the hanging surgical instruments, medical materials etc. It is possible to use different levels of Microwave power, UV-irradiation and treatment duration. The power supplied (≈1200 W, 220 V, 50 Hz) is the same as the usual domestic Microwave Oven. Only 100 W expenditure of Microwave power is required for the excitation of electrodlcss discharges in two lamps, and UV-irradiated flux is -48 Bact (λ=253,7 nm). The ozone is produced by UV-irradiation (λ=l85 nm).

The prototype (model) of bactericidal installation assembled on the basis of household microwave oven SP-18 ("Pluton" Company) was comprehensively tested. The sketch diagram of this installation is presented in Pig.8.

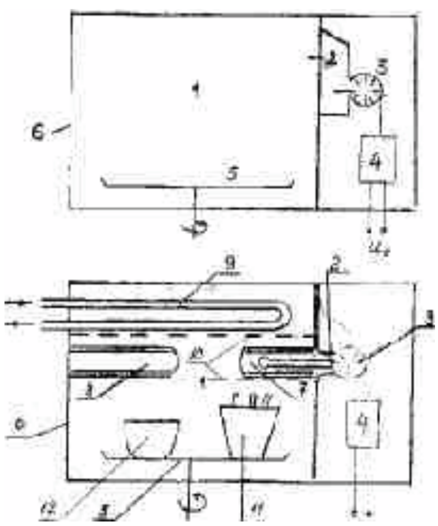

Figure 8. Microwave Oven (a), Bactericidal installation (b).

1 Working chamber (multymodc resonator), 2 - Microwave adapter. 3 - Magnetron M-155, 4 - Power supply block, 5 - Turning table, 6 - housing, 7 - UV-electrodless lamp (leading), 8 - UV-clcctrodle.ss lamp (driven), 9 - quartz tube (coil), 10-l,ight- and air-transparent RF-screen, 11 - UV-irradiated objects, 12 - Microwave heated object or liquid.

The module of irradiation unit consists of continuous operation mode magnetron (2450 MHz, 850 W), a coaxial microwave adapter, interchangeable clcctrodless Ar-Hg lamps of original design placed in the working chamber which is the multi-mode microwave resonator. The UV- and microwave transparent quart/ serpentine is placed in this chamber for treatment medical solutions and other (lowing liquids. A rotating table for installation irradiated objects (medical instruments, materials, vessels with different agents) is also placed in the working chamber. Electrodynamics principle of the coaxial microwave adapter provides stable operation of magnetron with variable non-stable microwave load and depression undesirable mode oscillations (including fifth harmonic) in the microwave spectrum. The lamp and adapter constructions arc shown at Fig.9, 10. This adapter is used as in bactericidal plant, so in Microwave-lighting module.

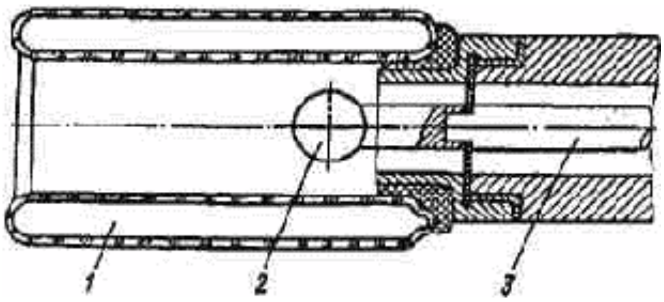

Figure 9. Ar-Hg electrodless UV-lamp - lamp, 2 Microwave exciter, 3 - coaxial guide (input).

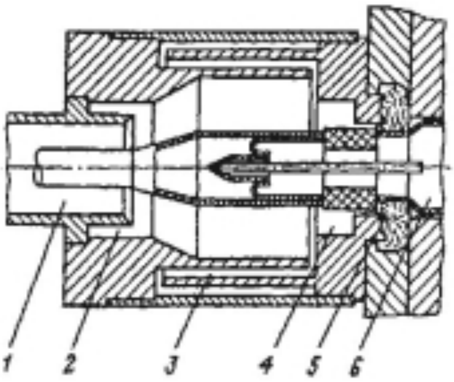

Figure 10. Coaxial microwave adapter 1 - Coaxial guide (output), 2 - 5th harmonic filter, 3 Microwave drossel, connection, 4 impedance trans former, 5 - contact gasket, 6 magnetron output.

5. THE CONCLUSION

The use of electrodless microwave discharge as a source of optical radiation in visible and UV-band of the spectrum is a perspective area of experts activity and promises in nearest and long-term future arising new updated products and systems for illumination and irradiation. There are, however, a lot of problems which are being a subject to solution, and today there is a lot of looked through possibilities, In the field of lighting systems of quasi-sun light and "colored" light the research and design works are already conducted.

The perspectives of creation of installation with microwave radiation power up to 20 kW in combination with strong UV-radialion and ozone treatment will be used for asepsis (purification) of drinking water or other substances, and also for asepsis of soil and reservoirs, having been infected, for example, in a result of the ecological catastrophes.