Electrodeless Microwave UV Lamps
Geometry, Spectra, Integrated Reflectors

For Multi-Lamp Microwave UV Systems

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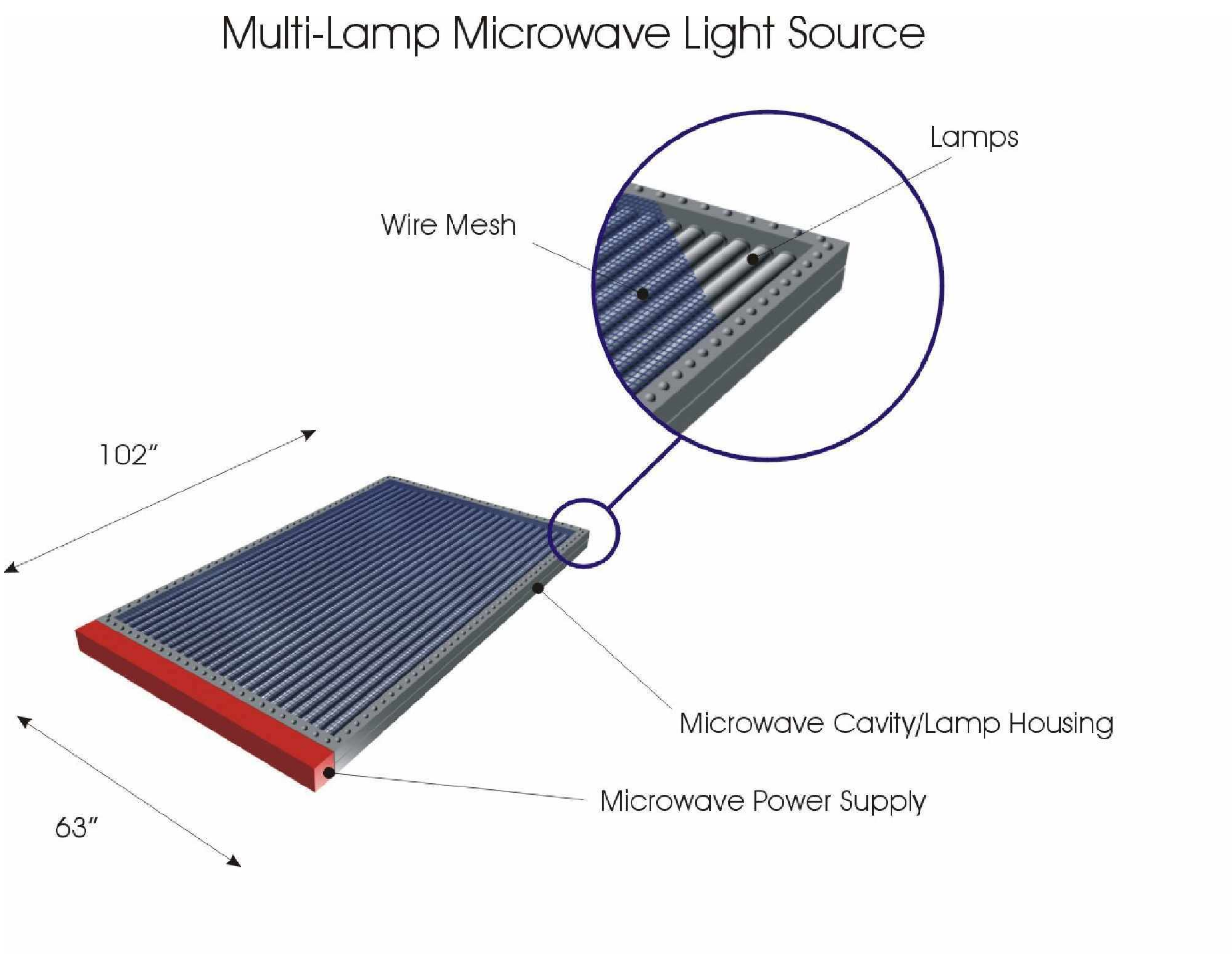

Figure 1. Basic idea of multi-lamp microwave UV light source.

Abstract.
Physics, technology and design of large diameter and length Electrodeless Lamps for Multi-Lamp Microwave UV Systems ("EL-Lamps") are discussed. Presented data on UV Spectra, output power, and reflectors configuration,

Multi-Lamp Microwave UV
Lighting System is shown schematically in the Fig.1. The System has large area microwave cavity. The cavity is made of metal mesh (at least one side) transparent for UV Light and not transparent for microwave radiation.

Microwave cavity in Multi-Lamp Microwave UV Systems
can be flat, cylindrical shape, rectangular, triangle or other shapes fitted for specific application. The cavity can be densely packed with regular Electrode UV Lamps or with specially designed microwave **Electrodeless Lamps ("EL-Lamps")**, made of glass or quartz. "EL-Lamps" are filled with inert gas or mixture of gases, emitting UV light produced by microwave discharge in the gas or by phosphor excited with gas UV emission. In order to get uniform excitation of many lamps in the same microwave cavity, the cavity should have dimensions satisfying formulae shown in our previous Article and the Patent [1]. Basically, the cavity volume should allow multi-mode excitation with amount of modes above some critical value. This amount is pretty large in practice and exceeds thousands of modes. Multi-Lamp Microwave Systems had been developed for Visible Lighting and industrial applications of UV Curing Technology for curing large area 3D objects, heat sensitive targets, wide web conveyors, and other applications, where low cost chemistry can be cured with spectrum matched UV light.

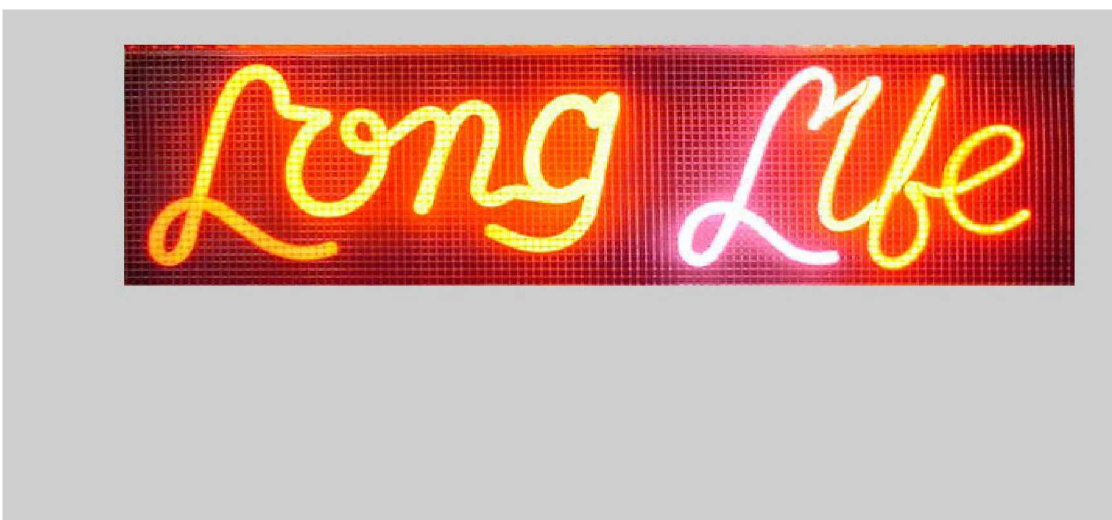

Fig. 2. Two "EL-Lamps" made in the shape of Artistic letters.

"EL-Lamps" developed for Multi-Lamp Microwave UV Systems are quite different from classic quartz microwave electrodeless lamps used in Single Lamp Microwave UV Systems.

1. “**EL-Lamps” can be made very big**.
   Length can be up to 96”, Diameter – 0.1 - 2 inches. “EL-Lamps” can be made cylindrical shape or many other shapes, including artistic letters (Fig. 2). “EL-Lamps” operating in glow discharge low pressure regime can be large Diameter and long Length and be the same size as regular fluorescent lamps operating also in glow discharge regime.

2. **Microwave Power Load**
   into ”EL-Lamps” of large size is much less than power load into the lamp in single-lamp microwave systems, which are much smaller and operate in medium pressure regime. As a result, surface temperature of “EL- Lamps” is maintained from 40-60C (low temperature mode) to about 200C (high temperature mode). As a result of low Power Load Lamps can be made of soft glass, as well as of hard UV glass, quartz and fused silica.

3. **UV emission of “EL-Lamps”**
   can be UV emission of: a) microwave glow discharge plasma, or b) UV light emission of phosphors, excited by plasma UV emission.
   UV emission spectra are line emission (Mercury Lines) if mercury is present, gas band emission if Excimer mixtures are used as a gas fill, or band emission of Phosphors. Thus, “EL-Lamps” emission spectra are line spectra (if mercury is present) or relatively narrow band emissions of excimer molecules or phosphors. As a result, “EL-Lamps” UV emission spectra can be precisely matched to the chemistry with use of blends of Phosphors, or proper gas mixtures, which can be selected in such way, when emissionspectra precisely coincides with spectra of photoinitiator excitation.

4. **Amount of “EL-Lamps” inside the same microwave cavity**
   can be from a few lamps up to 50-100 lamps and more (Fig. 3). Compact Multi-Lamp UV Systems are designed with area of uniform UV spot 20”× 36”, and 20”× 48”, which can be handled by one operator. These Systems have 10 -12 “EL-Lamps” per Unit.

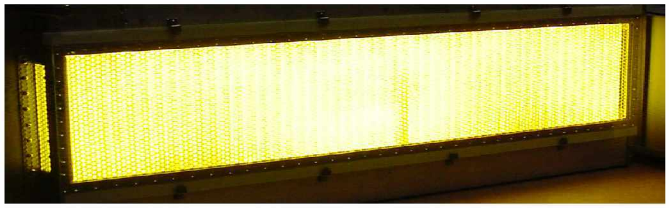

Fig. 3. Multi-Lamp Microwave UV System with 49 lamps.

Single-lamp microwave UV systems,
which are well known as the most powerful, efficient, long life and reliable UV light sources, have been widely used by the UV industry for decades.

UV windows of single lamp microwave systems have area 4”× 6” or 5”× 10”. Parabolic reflectors allow getting relatively uniform UV footprints about the same area size: 24 or 50 sq. inches. Using elliptical reflectors or defocused parabolic reflectors allows getting larger UV Spots. However, such larger UV footprints deliver UV light to the target no uniform, and create problems for even curing of complex form targets and targets of large size.

Multi-Lamp Microwave UV Systems Technology
discussed in our previous reports and publications [1] give much larger and more uniform UV footprints than Single-lamp UV Systems due to large amount of UV Lamps in the same UV Light Source. Uniform UV Spot under typical Multi-lamp UV System has area from 20”× 36” = 720 sq. inches or 960 sq. inches and above.

Unique feature of uniform large area emitters
allows realizing with Multi-Lamp UV System very uniform Irradiation of 3D Objects of arbitrary shape, because intensity at the target is almost the same for small distance from UV window and for long distance up to about distance equal to ½ of the width of UV window size.

For typical Multi-Lamp UV System with width 20" this distance is about 10 inches. This feature is successfully used for uniform UV Curing of 3D objects and objects with complex shapes.

"EL-Lamps" envelope materials,
as was discussed above, can be made not only from high temperature Quartz, but from low melting temperature glasses and low cost soft glasses widely used in fluorescent tubes industry. Soft glass has much less value of gas diffusion rate through lamp envelope than quartz. As a result, Lifetime of "EL-Lamps" is very long,
potentially up to 100,000 hours, as was proved by soft glass electrodeless lamps with RF Excitation [2].

There are four basic materials used for manufacturing of "EL-Lamps" for Multi-Lamp Microwave UV Systems:

Fused silica
(UV cut-off at 160 nm), **Ozone** producing deep UV "EL-Lamps", as well known,
Ozone, can be produced in Air (80% of Oxygen) by UV radiation with wavelengths below 185-220nm, which makes molecules O3 **Ozone** from O2 **Oxygen** molecules. **Ozone** molecules are very toxic, 100 times more toxic than well known for toxicity **Carbon Monoxide** molecules [4].

Doped quartz
(UV cut-off at 200nm) with additives reducing transmission below 200 nm. These are **Ozone free** UVC "EL-Lamps",

Hard UV Glass
(UV cut-off at 240nm), **Ozone free** UVC, UVB, UVA "EL-Lamps", capable to emit short wavelength UV down to 254 nm without producing **Ozone.** UVC "EL-Lamps", made of **Hard UV Glass** are cheaper than Lamps made of **Doped Quartz**.

Soft glass
(UV cut-off at 300nm), low cost, safe UVA lamps, free of UVC and UVB radiation.

Reflectors of "EL-Lamps" can be built-in inside the lamp. Temperature of "EL-Lamp" surface is low, as a rule, no more than 200C, and as a result reflective material deposited on the surface inside the lamp can stay without deterioration very long time. High temperature of quartz lamps in Single-Lamp UV Systems (900C) does not allow keeping reflectors inside the lamp. This is one of the reasons, why Single- Lamp Microwave UV Systems use external aluminum or dihroic reflectors. "EL-Lamps" built-in Reflectors direct UV light from UV lamp plasma and Phosphor to the target. There are Reflectors with wide window about 200 degrees and narrow windows with openings 30, 60, 90, and 120 degrees. Narrow windows give higher UV intensity on the targets at long distance above 20 inches. Wider windows give higher total UV power. Fig. 4 shows set of "EL-Lamps" inside the Multi-lamp Microwave UV System. "EL-Lamps" in the picture have 90 degrees window in built-in reflectors. These particular "EL-Lamps" have UV clear window, which is not covered by UV Phosphor. The same type of Lamp but made of fused silica and without Phosphor gives UV emission in 254nm (80%) and 185nm (20%), if it is filled with inert gas and mercury. Mercury can be introduced in metal or amalgam forms.

Fig. 4. “EL-Lamps” with 90 degrees clear window in built-in Reflectors (“A” type lamps) installed in 11-Lamp Multi-Lamp Microwave UV System.

“EL-Lamps” Spectra
can be selected by selection of gas fill (**excimer, mercury line “EL-Lamps”**) or by **Phosphor** deposited inside the lamp on lamp envelope surface. Phosphor can be removed from the Reflector window (A type lamp), or can be deposited on the lamp surface inside lamp tube on the window (R type lamp).

Excimer molecules
give emission at wavelengths[3]:
175nm - Xe2
193nm - ArF
248nm - KrF
308nm - XeCl
350nm - XeF
Excimer”EL-Lamps” are in R&D stage at present.

Mercury
atoms give emission at 185nm and 254nm lines [3]. “EL-Lamps”, made of doped Quartz or Hard UV Glass, which transmit UV light above 200-230nm, produce only one mercury line 254nm and do not make toxic Ozone. These lamps are used for surface modification and sterilization. “EL-Lamps” made of fused silica, give 185nm and 254nm radiation, produce Ozone, and are very efficient for surface treatment and modification. “EL-Lamps” made of soft glass are free from UVC and UVB radiation. These lamps emit UVA radiation with emission wavelength related with the intrinsic radiation of the Phosphor. Emission of Phosphor is excited by mercury lines 185nm and 254nm, which are trapped inside the lamp envelope. Fig. 5 shows typical UVA Phosphor emission spectrum and UVC spectrum of phosphor excitation. 254nm mercury line fits to the most efficient part of the excitation spectrum.

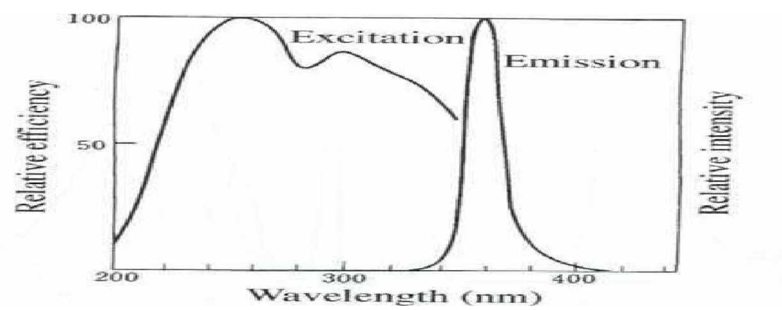

Fig. 5. Excitation and Emission spectrum of typical UVA Phosphor [3].

Lamps with Phosphors. Spectrum matching.
Soft glass does not transmit 185nm and 254nm wavelengths. Soft Glass “EL-Lamps” with inert gas and mercury fill are used in combination with different UV Phosphors deposited on the lamp envelope surface inside the lamp. These lamps do not produce UVC and UVB radiation at all, and give most of UV emission at the specific UV Phosphor band.

UV Phosphors
are available today for covering UV spectrum from about 260nm to 450nm. Blends of Phosphors allow combining spectra of individual Phosphor into wide band, dual or triple band spectrum, which can be precisely matched to the most efficient UV
Curing spectra of the chemical formulation. “EL-Lamps” with different phosphors can be excited in the same Multi-Lamp microwave UV System. This feature allows creating combination spectrum just by filling the System with “EL-Lamps” with different Phosphors. Variety of existing “EL-Lamps” can be used to match UV Lamps Spectra to the Chemistry and help chemists to develop new formulations without matching them to the UV lamps. Typical Spectra of a few UVA “EL-Lamps” are shown in the Fig. 6

Phosphors used in “EL-Lamps”
as well as in many regular electrode fluorescent UV Lamps, are widely available, emit relatively narrow band spectra, which cover every wavelength between
260nm and 450nm. We give short list of a few popular phosphors used today in UV industry [4].

Table1. List of popular UVA and UVV Phosphors.

Chemical formulae	Emission Wavelength, nm	Emission band halfwidth, nm	Band
(Ca,Zn)3(Po4)2:Tl+	310	40	UVA
Ca3(PO4)2:Tl+	328	40	UVA
BaSi2O5:Pb2+	350	40	UVA
SrB4O7F:Eu2+	360	16	UVA
(Ba,Sr,Mg)3Si2O7:Pb2+	370	60	UVA
SrMgP2O7:Eu2+	394	25	UVV
Sr2P2O7:Eu2+	420	30	UVV

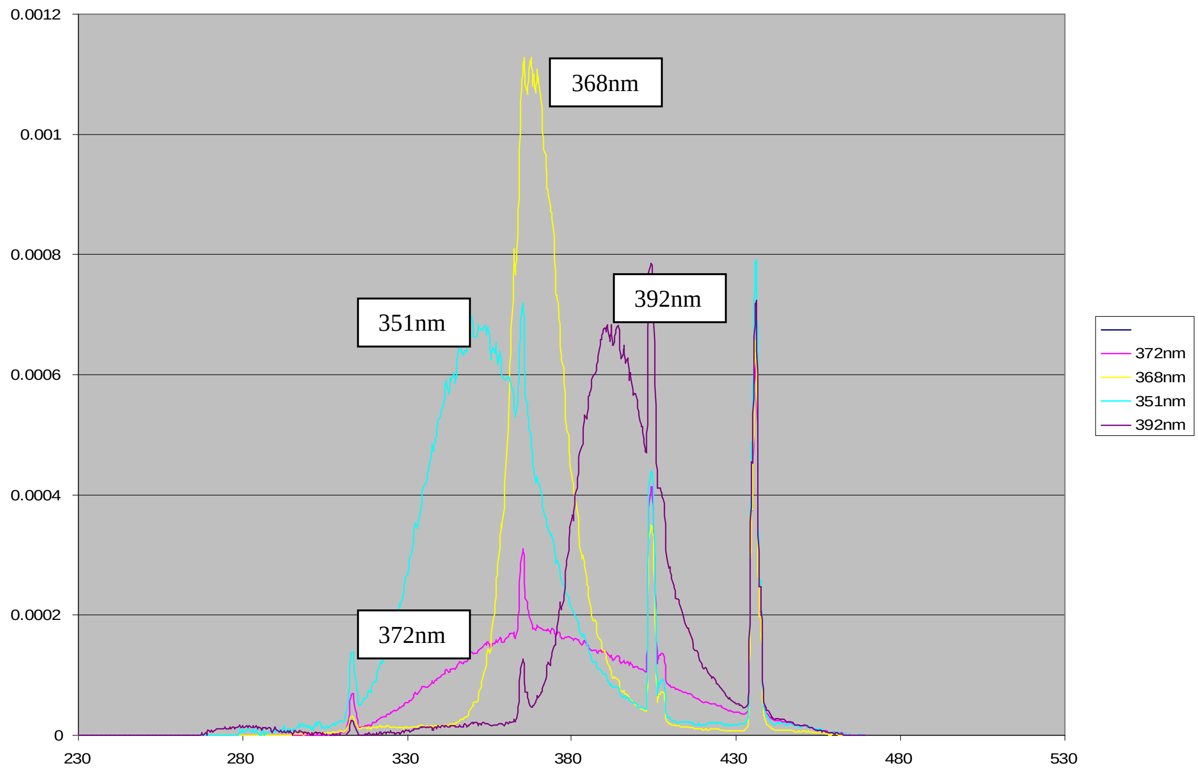

Figure 6. Typical Spectra of a few electrodeless microwave UVA "EL-Lamps"
Horizontal scale—nm, vertical scale—intensity in relative units.

Lamps IR Emission.

Many applications with heat sensitive substrates (no supported film, electronic chips) require low IR Emission from the UV Source. "EL-Lamps" with proper cooling are capable to keep substrate temperature below 40-50C without special substrate cooling. However, some applications (automotive refinishing, for example) need warming the substrate before chemistry spray, and UV Curing under elevated temperature. This kind of UV Curing can be done with special High Temperature "EL-Lamps" made of Hard UV Glass, Quartz, and Pyrex. This kind of "EL-Lamps" in the Systems with Low/High Temperature regimes allow to elevate substrate temperature up to 70-80C in 5-10 min without use of external IR Lamps. "EL-lamps" made of microwave absorbing glass allow getting extra IR emission and making UV/IR curing.

UV-Radiation Safety with "EL-Lamps".

There are government guidelines and threshold limit value levels of safe exposure for UV radiation. Permissible exposure levels are quite different for different wavelengths. The most dangerous wavelength band is UVB band from 270-290nm. Eight hours exposure at this wavelengths, according to ACGIH [5], is permissible with average irradiance no more than 0.1 µW/cm2. This is a very low UV-irradiance level. However, if a UV band centered at 368nm is used, the average safe irradiance during eight hours will be 10,000 times higher and can reach 1 mW/cm2. Exposure under 1 mW/cm2 at 368nm during 8-hour working day is safe [5], and equivalent to the 3 second exposure under 280nm radiation. Quartz and Fused Silica "EL-Lamps" produce toxic Ozone and should be used in combination with catalytic Ozone Destructors.

Phosphor coated "EL-Lamps" made of Hard UV Glass have 254nm line component, which can be up 1-2% of the UVA emission power. In some cases, this UVC component is useful for encapsulation of the curing material surface from Oxygen, and reduction of UV Exposure time. If safety is important issue (Automotive Shops), but Hard UV Glass lamps should be used for target warming, UV System window can be covered with thin clear plastic film, transparent for UVA and IR radiation but opaque for 254nm wavelength.

There are phosphors with high and efficient emission at 368nm and practically zero emission below 350nm (Figure 5, 368nm spectrum). These phosphors, as well as phosphors with peak emission at longer wavelengths, can be safely used in multi-lamp microwave UV-curing systems for automotive refinish and construction industries.

UV Intensity on the Target in mW/cm2 can reach 50 mW/cm2 for 368nm "EL-Lamps" at 6" distance. Less efficient UV Phosphors may give UV Irradiance up to 30 mW/cm2 at 6" distance. Efficient and uniform UV Curing under Multi-Lamp Microwave UV Systems even with relatively small size 20"×36" can be done with distance from UV Window to the Target up to 18".

Conclusions

Electrodeless Lamps ("EL-Lamps") in Multi-lamp microwave UV systems can be useful in the following industries and processes.

- Automotive and construction industries where UV safety is crucial.
- Processes where excessive heat transfer to the target is critical (LCD displays, plastic medical devices and semiconductors).
- 3-D and large-area footprints UV Curing including airplanes, automobiles, furniture, boats, etc.
- Applications and processes requiring low-cost UV-curing units, UV lamps and UV-curing consumables.
- Processes where using long life UV lamps is vital (automotive conveyors).

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