Multi-Lamp Microwave UV Systems
Physics and Technology

By Vlad Danilychev

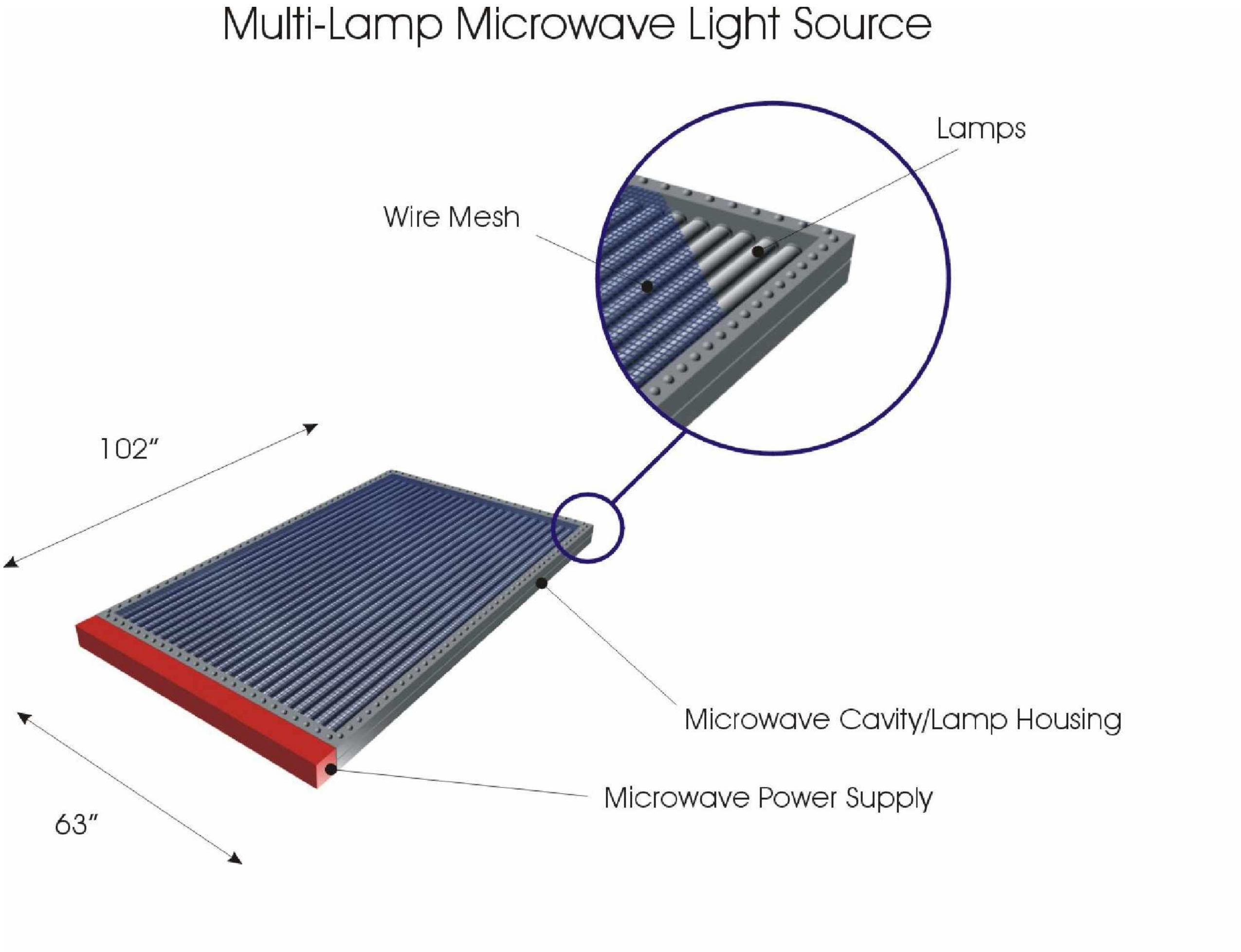

Fig. 1. Basic Idea of Multi-Lamp Microwave UV Light Source.

UV Industry - New needs.
Single-Lamp Microwave UV System is well known as the most powerful, efficient, long life and reliable UV Light Source widely used by UV industry for decades. However, there are growing fields of UV Curing Applications, which requested large area UV Systems (3D objects, including automobiles, airplanes, furniture, and constructions), Low Heat (Displays, Films, Medical Plastics), Precision Spectrum Matching (Low Cost Chemistry), Long Life (UV Curing Tunnels at Automotive Conveyors), and low cost lamps (Automotive Body Shop Market).

UV LED Technology developed during last few years makes UV LED's as a one of potential candidates for Applications in the fields listed above. UV LED's can be assembled in multi-element panels with uniform large area emission. The only problem of high area UV LED light sources is related with high cost of such large area UV Systems.

Fluorescent UV Lamps are relatively low cost, can be made with variety of preset UV Spectra (different UV Phosphors), do not emit IR (heat), and have life time longer than mercury ARC UV lamps. Each Fluorescent UV lamp needs ballast to power the lamp. Multi-Lamp Systems should have large amount of ballasts, wires and electrical contacts, which may reduce reliability of the Multi-Lamp UV System based on UV fluorescent lamps powered with ballasts.

Microwaves can exit fluorescent UV Lamps. However, it is well known that it is impossible to run even just 2 lamps in parallel by the same ballast or run 2 lamps simultaneously inside the same microwave cavity with one or a few fundamental modes (cavity electromagnetic field configurations): one lamp will start, but others never - electric voltage or microwave electric field shall jump down after ignition of the first lamp, down much below the ignition voltage necessary for starting the second lamp.

Theory shows that if amount of modes in the microwave cavity high enough, higher than certain critical number [1] it possible to load power into almost mutually independent loads in the cavity. In practice it means, that physical Volume of the microwave cavity V should be larger than certain critical minimal volume Vcrit for such multi-load operation:

$V > V_{crit} = k 8 \pi \lambda^3 / 3$, where:

k - numerical coefficient with value ≥ 1.0
π – 3.14
λ – wavelength of the microwaves

If more than 1 lamp is excited in the multi-mode microwave cavity with Volume $V \geq V_{crit}$, the first lamp ignition does not suppress electric field in the vicinity of other lamps below ignition level – and all lamps run simultaneously in spite of negative voltage-current characteristic of electric discharge in gases. The extreme case is open space – under powerful microwave beam it is possible to excite many lamps simultaneously.
It had been found experimentally, that very high critical amount of modes necessary for multi-lamp excitation can be reached in relatively small cavities – as small as 1 cubic foot volumes for industrial microwave wavelength $\lambda = 4.8$", and in relatively flat designs, shown in the Fig. 1.
If we go to higher microwave frequencies than the most common industrial microwaves 2.45 GHz ($\lambda = 4.8$"), we satisfy multi-lamp excitation conditions even in smaller cavities.

Many low pressure discharge lamps, as well as medium pressure lamps can be excited in multi-mode cavity if Volume of the cavity is large enough. The most uniform excitation in multi-mode cavities can be easily achieved with low-pressure fluorescent and germicidal mercury lamps with lengths from 1 inch to 96" and above and diameters from a few mm to 1.5-2.0". Microwave excitation of many low-pressure electrodeless lamps can be done with much higher input power per unit of lamp volume than it is possible with regular electrode lamps powered with ballasts. Electrode lamp power is limited by cathode emission currents, and can be increased only with special bulky and high cost cathode structures. So, electrodeless lamps can run with much higher power than the same size electrode lamps.

UV output power of Multi-Lamp Microwave UV System is higher than power of regular Multi-Lamp UV system powered with ballasts, and lamps can be stacked in much denser packages in UV panels as shown in the Fig. 2. The UV intensity can reach 40 mW/cm2 uniformly at the full area of Lamp Cartridge. Distribution of the intensity across 25” wide and 43” long Multi-Lamp Microwave UVA Curing Unit is shown in the Fig. 3.

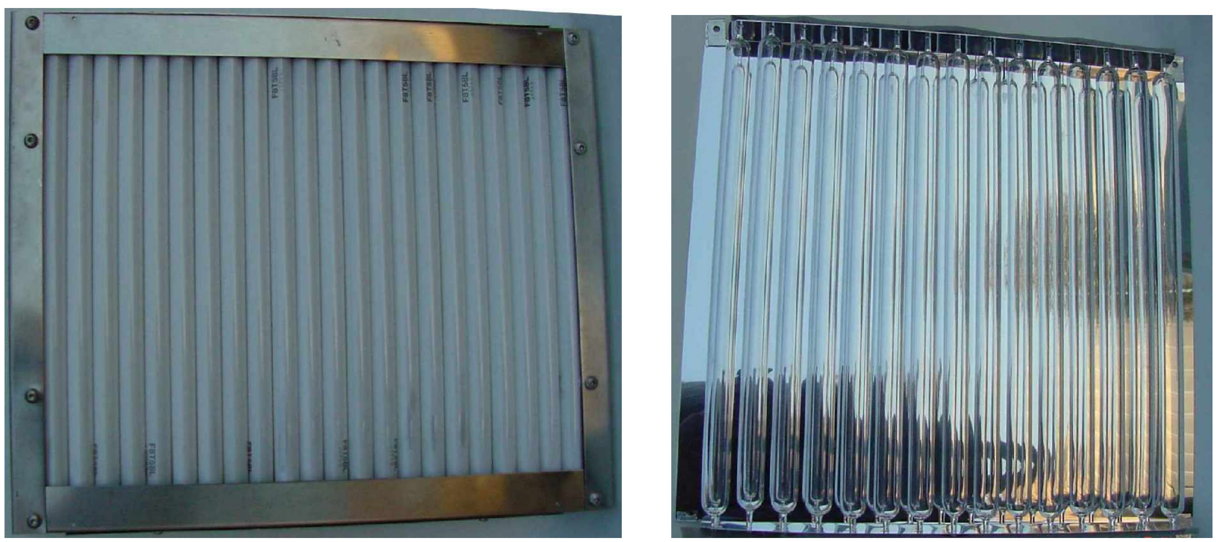

Fig. 2. UVA (left) and UVC (right) microwave lamp cartridges. UVA: 300-400nm. UVC: 185 & 254nm

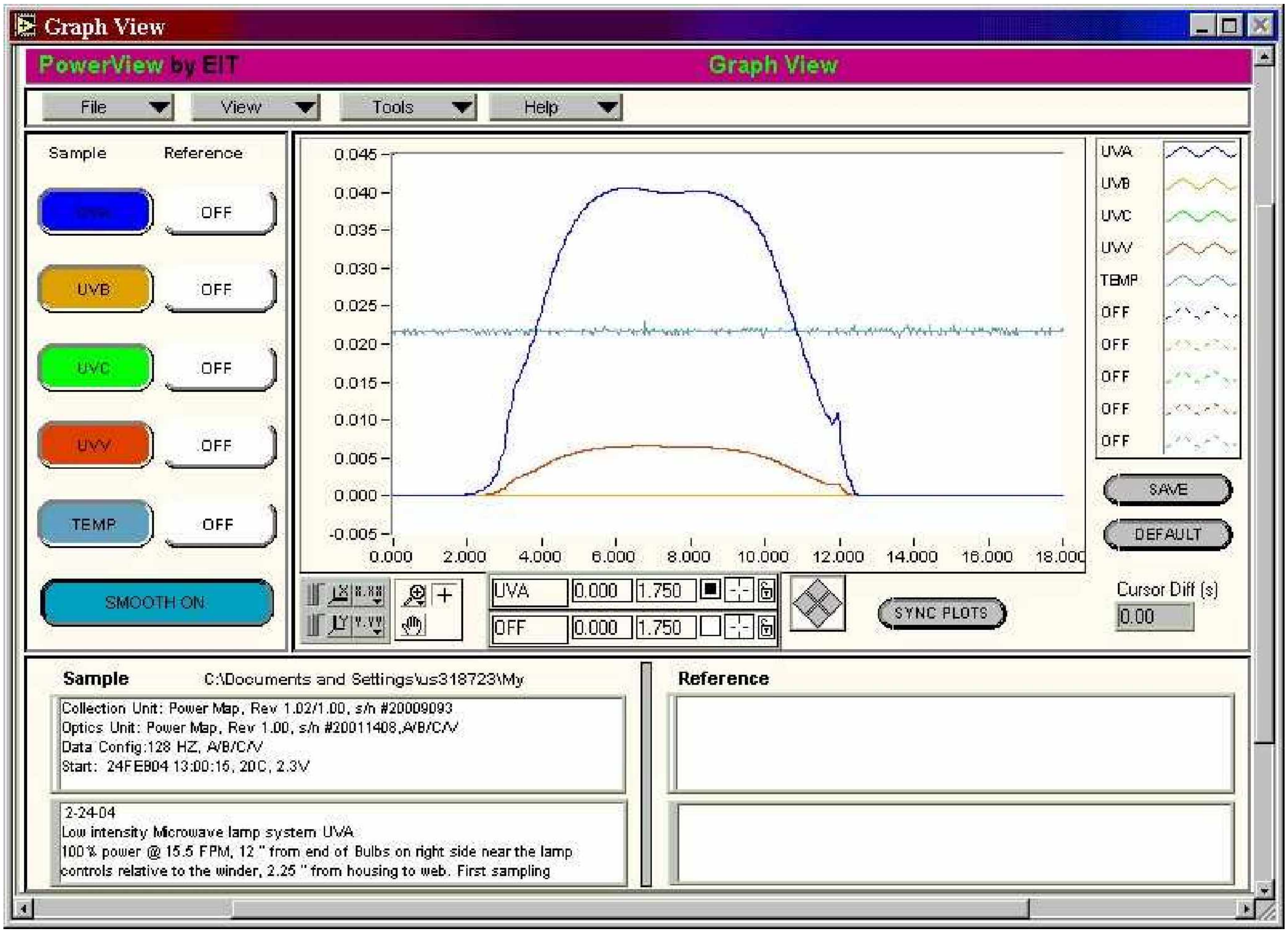

Fig. 3. UV Intensity distribution across UV window of Multi-Lamp Microwave UV System.

Absence of cathodes and electrical wire/glass feeds makes lifetime of electrodeless fluorescent lamps much longer than regular electrode lamps.
Glass (especially at temperatures below 100C) has negligible diffusion coefficient of gases through the lamp envelope. Gas diffusion through cold glass is many orders of magnitude less than the diffusion through quartz at 850-900C temperatures typical for ARC Mercury lamps or Microwave lamps in High Intensity Single-Lamp Systems.

RF excited electrodeless fluorescent lamps as it had been shown in Lighting Industry, have lifetime more than 100,000 hours.
These lamps demonstrated 65% of initial light emission power after 100,000 hours of operation [2]. Long life of Electrodeless Fluorescent Microwave UV Lamps running in Multi-Lamp Microwave UV Systems makes these lamps as the primary candidates for UV Tunnel Automotive Conveyors. These conveyors could not be stopped just for replacement of dead lamp.

UV Spectra of Electrodeless Microwave Fluorescent Lamps can be easily constructed with blends of large variety on-shelf available UV phosphors. These Spectra can be precisely matched to the UV Curable Chemistry Formulation Spectra.

This feature opens **"**spectrum matching**"** possibility to the chemical industry. Formulators can dictate what specific spectra should be used for efficient curing of specific chemistry. "Spectrum matching" can reduce UV curing dosage down to 10 times relative to dosage required for curing by wide spectra regular high power UV lamps.

Spectra of electrodeless microwave lamps at deep UV (UVC 185nm and 254nm) are mercury line spectra. These systems are operating in compact Flood Unit Designs as well as in large area flat UV panels with 25"×43" output area in large Multi-Lamp Systems. Microwave Electrodeless 254nm UVC Lamps are available in Ozone-free Hard Glass Envelopes with Reflectors integrated inside the lamps. New deep UV Systems (R&D stage) will use mercury free electrodeless Excimer lamps with band spectra from 175nm to 351nm.

Spectra of electrodeless microwave UVA lamps are shown in Fig. 4. These lamps are built with Reflectors integrated inside the lamps.

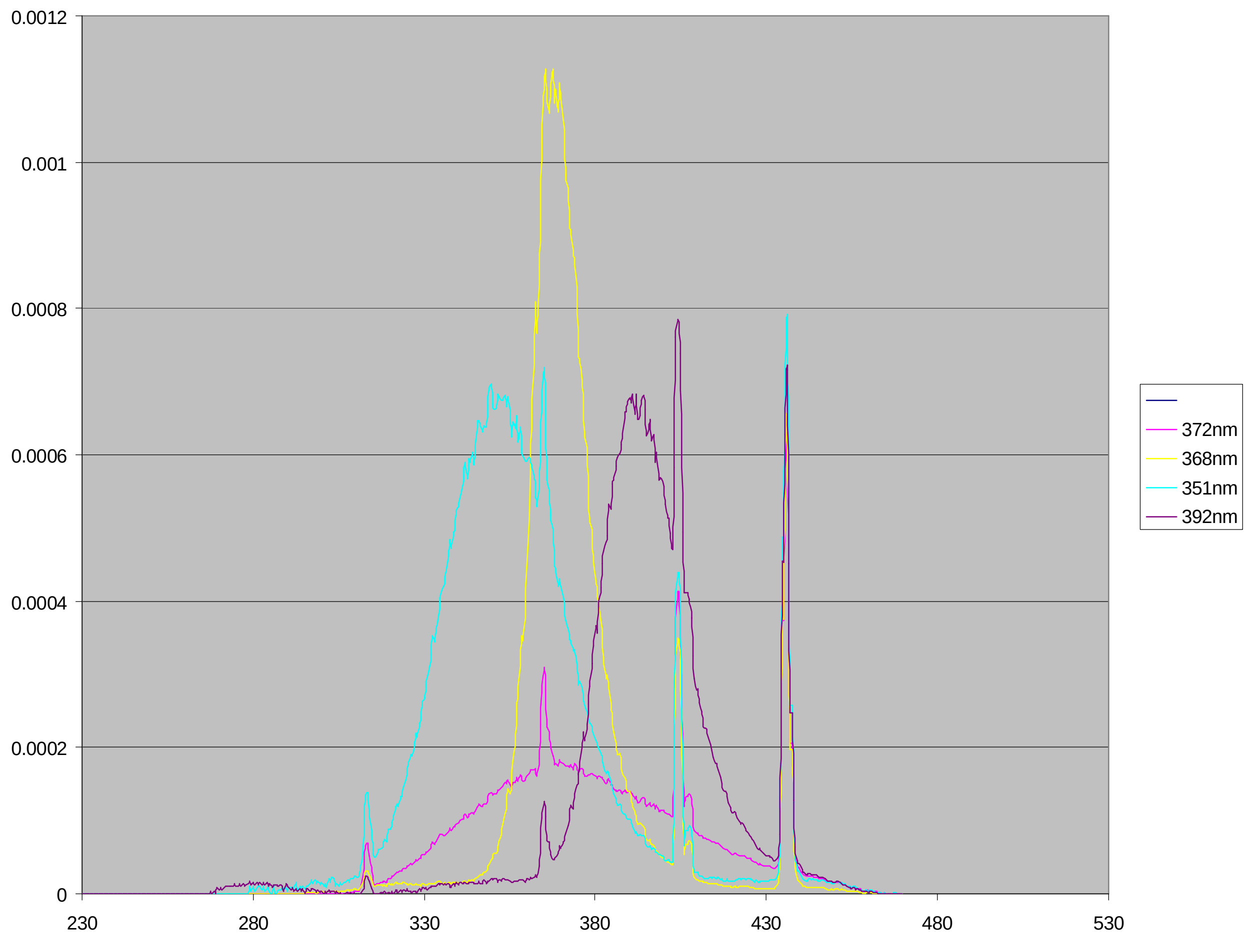

Fig. 4. Spectra of Electrodeless Microwave UVA lamps. Horizontal scale – nm, vertical scale – Intensity in relative units.

The most efficient, high power, and low cost Microwave Generators are based on CW Magnetrons.
Relatively high power and high cost magnetrons (300-500W) should be used for excitation of high power electrodeless UV lamp in Single-Lamp microwave system. High power microwave lamps in Single-Lamp Microwave UV Systems should be made of Quartz and require 300-600 W/inch level of power for efficient excitation. Large Multi-mode cavities in Multi-Lamp Microwave UV Systems can be excited with low cost 1 kW Magnetron and multiple 1 kW magnetrons. Dual magnetron Multi-Lamp UV System Power Supply and Lamp Cartridge is shown in the Fig. 5.

Fig. 5. Dual Magnetron 25”×43” Output UV Window Multi-Lamp UV System. Magnetron power Supply and Lamp Cartridge are shown.

High Voltage Magnetron power supplies developed for lightweight UV Curing units used for Auto Refinishing are based on compact Solid State Circuits. One of such HV Solid State Power Supplies is shown in Fig. 6.

Fig. 6. 1.5 kW High Voltage Solid State Power Supply for running 1 kW magnetrons.

UV Radiation safety was studied during decades.
There are Government Guidelines and TLV's levels of safe exposure of humans by UV Radiation. Permissible exposure levels are quite different for different UV wavelengths. The most dangerous wavelength band is UVB band from 270nm to 290nm. 8 hours (working day) exposure at this wavelength according to ACGIH [3] is permissible with average Irradiance no more than 0.1 μW/cm2. This is very low UV intensity level. However, if UV band centered at 368nm is used - the average safe Irradiance during working day (8 hours) will be 10,000 times higher and can reach 1 mW/cm2. It means, that exposure under 1 mW/cm2 at 368nm during working day is safe [3].

There are phosphors with high and efficient emission at 368nm and practically zero emission below 350nm (Fig. 4, yellow spectrum). These phosphors, as well as phosphors with peak emission at longer wavelengths can be used in safe Multi-Lamp Microwave UV Curing Systems for Automotive shops, Refinishing plants, construction industry, and so on.

Multi-Lamp Microwave UV Systems can not compete with High Intensity Single-Lamp UV Systems in high speed processes (600 f/min), in curing Highly Sensitive to Oxygen Formulations, or in any UV Curing process with high level of minimal UV Intensity for efficient curing.

Maximum UVA intensity achievable at present state of the art with Multi-Lamp Microwave UV Systems is at the level of 50 mW/cm2. This value is 10-50 times less than UVA intensity reached with High Power Single-Lamp Microwave Systems at the focal line of their elliptical reflectors.

Areas of UV Industry, in which Multi-Lamp Microwave UV Systems can be useful and competitive:

- Industries, where UV safety is crucial (Automotive shops, construction industry)
- UV Curing processes, where excessive heat transfer to the target is critical (not supported films, LCD Displays, Medical Plastics, Semiconductors)
- UV Curing of 3D and large area objects: Airplanes, Automobiles, Furniture, Boats, and etc.
- UV curing applications and processes requiring low cost UV Curing Units, UV Lamps, and UV Curing consumables
- UV Curing processes where using long life UV Lamps is vital (Automotive conveyors)

2005 development for Automotive Refinishing Industry is shown in the Fig 7. This is Multi-Lamp Microwave UV System with 40 lbs UV Head, 20”×36” output uniform emission area, 40 mW/cm2 UV Intensity, safe 368nm UVA band, and variable UV power.

Fig. 7. Multi-Lamp Microwave UV Unit. 10 Electrodeless Microwave UVA lamps with reflectors integrated inside lamps are used in this UVA Light Source.

Parameters of typical UV lamps and corresponding UV Systems including: Single-Lamp Microwave, Mercury Arc Lamps, XENON Flash Lamps, and Low Pressure Fluorescent UV Lamps are discussed in many publications [4].

Table I shows typical parameters of Microwave Electrodeless Lamps used in Single- and Multi-Lamp Microwave UV Systems in comparison with parameters of other UV lamps.

TABLE I. Parameters of typical UV Lamps.

Lamp Parameter	**Electrodeless Single-Lamp Microwave**	**Electrodeless Multi-Lamp Microwave**	**Mercury Arc Electrode Lamps**	**XENON Flash Lamps**	**Electrode Fluorescent Lamps**
Power Load, W/inch	300-600	1-30	300-600	100-300	0.5-5
Lamp Temperature, Degrees C	900	40-120	900	500-800	40-60
Available Spectra, nm	Continuum 185-500nm	185, 254nm, and/or Any band in 270-500nm	Continuum 185-500nm	Black Body Spectra Centered at 500nm	185, 254nm, And/or any Band in 270-500nm
Lamp Length, inches	3”, 6”, 10”	Any length from 6” to 96”	Any length From 3” to 64”	Any length from 1” to 24”	Any length From 6” to 96”
Lamp Life Time, hours	From 5,000 to 8,000	From 10,000, Potentially up to 100,000	From 1,000 to 3,000	From 250 to 500	From 3,000 to 10,000
Lamp Material	Quartz	Soft/Hard Glass, Quartz	Quartz	Quartz	Soft/Hard Glass, Quartz
Failure: Catastrophic	Yes	No, Gradual decay	Yes	Yes	Yes
Spectrum Matching Capability	No	Yes	No	No	Yes
OZONE	Yes	Free choice: Yes or No	Yes	Yes	Free choice: Yes or No
IR Radiation	Yes	No	Yes	Yes	No
Reflectors	External, Elliptical or Parabolic	Built-in Inside the Lamp	External, Elliptical or Parabolic	External, Flat, Elliptical, or Parabolic	External or Built-in inside The lamp
Intensity with External Reflectors, W/cm2	Up to 2 W/cm2 in UVA, UVB bands	N/A, large area flood up to 50mW/cm2 in UVA band	Up to 1 W/cm2 in UVA, UVB bands	Pulse. Up to 50 W/cm2, Peak in UVA band	Up to 5mW/cm2 in single lamp systems
Flood Intensity, W/cm2	Up to 150 mW/cm2 in UVA, UVB	Up to 50 mW/cm2 in UVA	Up to 100 mW/cm2 in UVA, UVB	Pulse. Up to 1 W/cm2, Peak in UVA	Up to 2-5 mW/cm2 in UVA
Output UV Window Area	4”×10” max	From 12”×12” up to 48”×96”	From 4”×10” up to 6”×64”	From 3”×3” up to 6”×24”	From 12”×12” up to 48”×96”

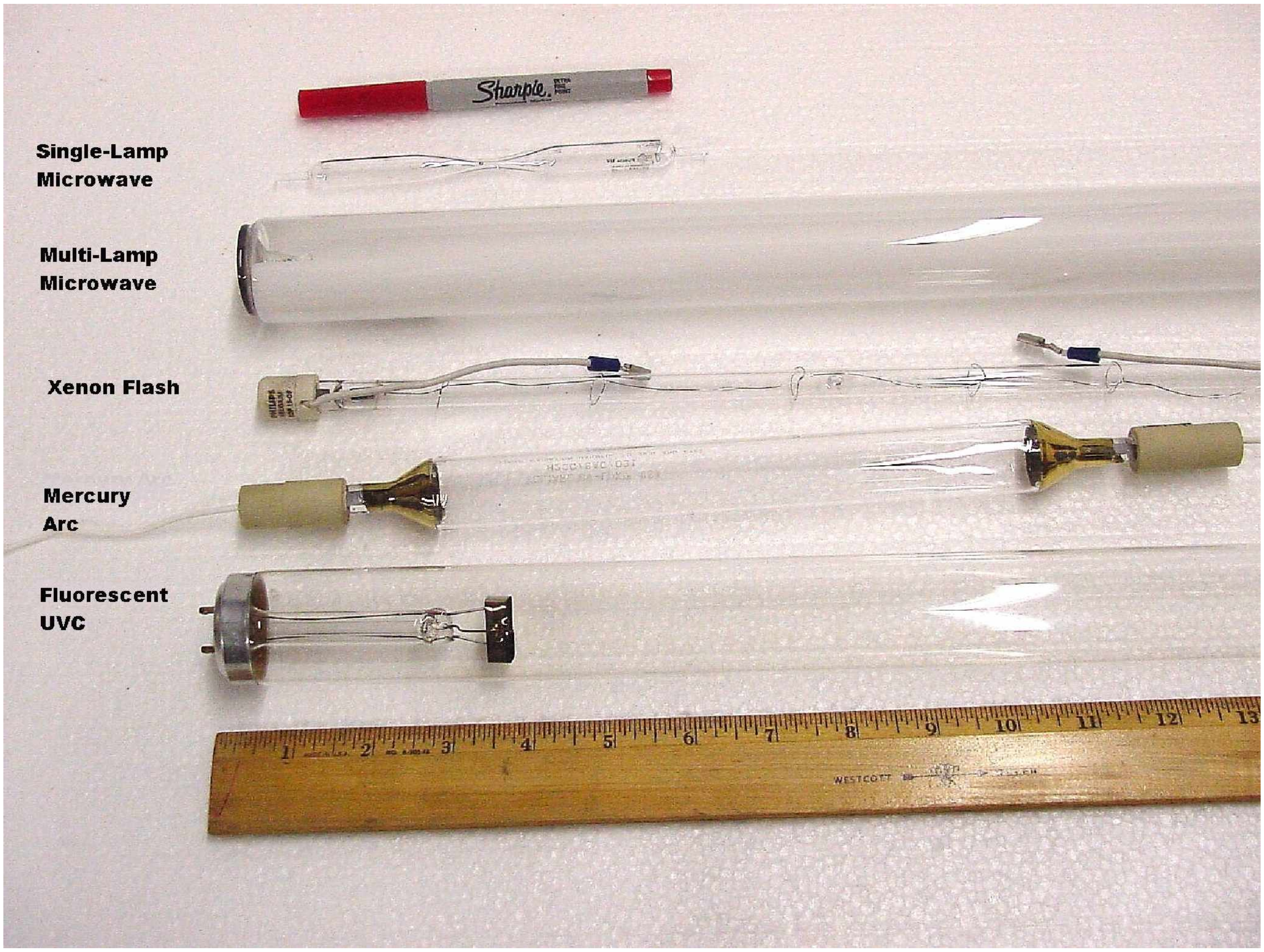

Fig. 8. Photos of typical UV Lamps.

References:

1. US Patent 5,931,557.
2. ICETRON, Inductively coupled Electrodeless System. Page 2. Osram Sylvania Product Bulletin FL 021. www.sylvania.com.
3. Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents and Biological Exposure Indices (BELs). ACGIH. ISBN: 1-882417-11-9. acgih_tech@pol.com.
4. Roger Phillips. "Sources and Applications of Ultraviolet Radiation." Pages: 185-332. Academic Press, Inc. New York, 1983