Microwave Excitation of Fluorescent Lamps

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Abstract— *The excitation of a commercial fluorescent lamp is obtained with easy using a coaxial dipole antenna placed along its external surface. We present the results obtained making direct comparison between the luminous flux emitted by a commercial fluorescent lamp fed with 220 V ac power or, alternatively, with microwave power at 2.545 GHz. The luminous efficiency attainable with microwaves and details on the associated technology are reported. An account of the possible advantages of the novel method of excitation are also given in view of the construction of fluorescent lamps of industrial and civil interest.*

Keywords— fluorescent lamp, microwave methods, electrodeless lamp.

I.   INTRODUCTION

Fluorescent lamps and light emitting diodes actually seem to play a major role in lighting industry in view of large scale industrial and civil applications. Their peculiar advantages and disadvantages, though, do not give a simple and clear cut answer to the fundamental question as to which technology is definitely the best for large scale lighting application. The luminous efficiency of a lamp based on one of these two technologies is an important parameter to deal with. However, it cannot be considered by itself the first and only criterion of choice. Lamp duration, temperature effects, age derating, lumen depreciation, number of switching, environmental working conditions, color rendering, modulation capability, environmental impact and costs are relevant parameters to deal with. A comparative life cycle assessment of luminaires for general lighting, i.e. compact fluorescent lamp vs Light Emitting Diode was performed (Principi, 2014). In this context the luminous efficiencies of fluorescent lamps, ranging from 40 lm/W to 100 lm/W, are still attractive, so that new excitation methods, new phosphors linings and different gaseous fillings are currently studied in scientific and industrial laboratories. Cavity-less and electrode-less methods of excitations are investigated as well, aiming at obtaining visible emitting lamps of higher efficiencies, a longer life span and reduced costs.

Previous work done at the National Institute of Optics, INO, for the construction of a microwave driven cavity-less mercury UV lamp, demonstrated the high luminous yield, reporting on the relevant characteristics of the plasma discharge dipole driven lamp (Ferrari, 2013). A microwave driving coaxial dipole antenna was placed into a recess of the glass bulb, resulting very efficient for UV light production in comparison with a germicidal low pressure commercial arc lamp having the same sizes. However, when the applied power was greater than a few tens W at 2.45 GHz the microwave lamp needed air or water cooling.

The present study is performed to verify the possible advantages of applying the cavity-less and electrodeless microwave method for the construction and the excitation of a fluorescent bulb useful for lighting purposes without placing the antenna into a recess of the bulb. To this end experiments are done to verify that the plasma discharge inside a commercial fluorescent bulb with ordinary gaseous and Hg filling can be excited with microwaves simply placing the coaxial cable antenna externally and in proximity of the bulb, and, at the same time, to verify that the attainable luminous efficiency can be of industrial interest.

Some curiosity driven experiments initially performed using commercial fluorescent tubes of various geometrical shape and trade-marks suggested to get deeper insight into the matter without attempting to construct a bulb of special design.

Accordingly, we made direct comparison between the luminous visible emission of a commercial lamp excited externally with microwaves and the emission of the same lamp fed with 220 V ac.

II.   EXPERIMENTAL

The experiments were made placing the lamp inside an integrating sphere. The experimental set-up is shown in Fig. 1
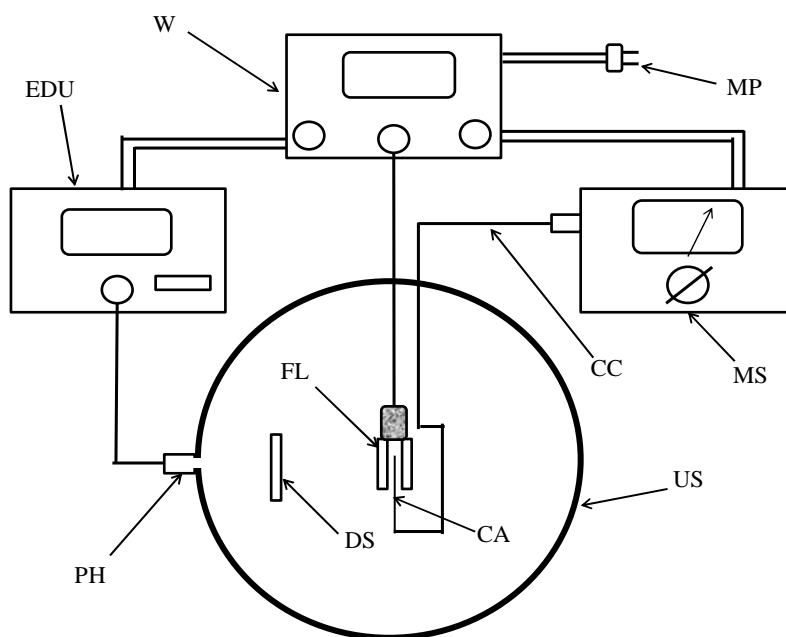
Fig. 1: Scheme of the experimental set-up. CA: coaxial antenna; CC: coaxial cable; DS: direct light shield; EDU: electronic display unit; FL: fluorescent lamp; MP: mains plug; MS: microwave 2.45 GHz source; PH: photometer head; US: integrating sphere; W: ac wattmeter

In the scheme of Fig.1 US represents the integrating sphere (Ulbricht Sphere mod. LMT Lichtmesstechnik Berlin, Gmbh), 2 m in diameter. It was equipped for luminous flux measurement of light sources in a wavelength range from 400 nm to 700 nm. The diameter of light sensitive area of the photometer head, PH, was 30 mm. A suitable shield DS impeded direct light to reach sensor PH. Electronic display unit EDU was a model LMT U 1000 with a display range from 10^{-3} lm (last digit) to 2×10^5 lm. The dipole antenna, CA, shown in

foreground of Fig. 2, was made out of a commercial 3.58 mm semi-rigid 50 ohm coaxial cable (UT 141 Micro-Coax Pottstown, PA, USA) having an average power handling capability of 250 W at 2.45 GHz and maximum operating temperature of 125 C . The antenna, connected to the output port of MS, was 136 mm long, provided with a SMA connector at one end and with an exposed 20.1 mm dielectric tip (inner conductor with dielectric lining) at the other (active) end.

Fig. 2: Coaxial dipole antenna attached to the output port of microwave source. The dielectric-tip end is evident in the foreground.

The antenna was constructed by simply stripping off the outer conductor of a regular semi-rigid coaxial line to expose the inner conductor by a quarter-wavelength. This antenna does not emulate a standard symmetric dipole antenna, being rather definable an asymmetric □/4 radiator. The brass □/4 sleeve choke placed near the antenna coaxial connector, as Fig. 2 shows, is a device commonly utilized to block backward reflections from the antenna load, but in our experiments it revealed utterly useless.

The coaxial antenna was placed in between the two "U" shaped active arms of the fluorescent lamp, FL, (Beghelli, mod. Compact 6000, 15 W, 2700 K) in axial position, as Fig. 3 shows.

Fig. 3: The dipole antenna is placed along the axis of the fluorescent lamp.

The lamp was made out of two parallel U-shaped fluorescent tubes, 11 mm in external diameter, 96 mm in length, attached to a standard E27 thread socket. The space between the fluorescent tubes was sufficient to accommodate the antenna CA placed on the longitudinal axis of the lamp, centrally located between the tubes, as shown. The radiating end of CA was nearly in contact, but not in touch with the socket. Small axial and angular displacements of the antenna enabled very good impedance matching, the reflected power being negligible. The clearance between the antenna external conductor and the fluorescent tubes was ≤ 1 mm.

The lamp, attached to its feeding cables, (microwave and 220 AC), was attached to a small open rig hanging from the ceiling of US, in central position, as depicted in Fig.

1. This mounting enabled immediate microwave or 220 V excitation of the lamp without any displacement of the components inside US. Microwave power was applied using a magnetron source, MS, having 100 W of maximum output power at 2.45 GHz (mod MPG 4M Opthos Instruments Inc, Rockville, MD USA), provided with a coaxial output as Fig. 2 shows. Forward and reflected microwave power were measured using a calibrated microwave power meter (Bird Electronic Instruments, Cleveland Ohio, USA, Mod 43 wattmeter, not shown). Fig. 4 shows the fluorescent lamp excited with microwaves. The luminous emission from the fluorescent lamp was nearly uniform and the bulbs were lit all along their length.
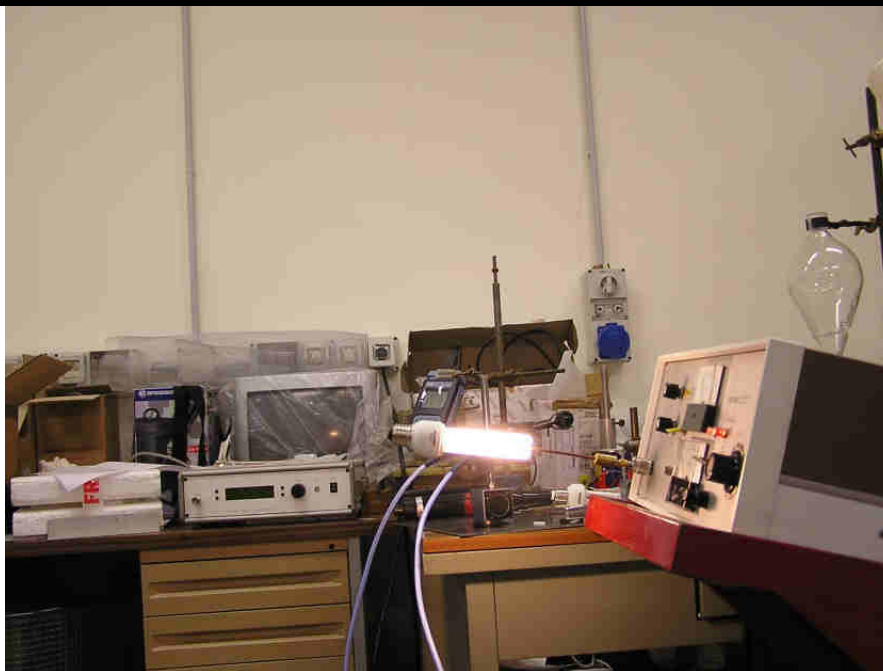
Fig.4: The commercial fluorescent lamp is on, fed with microwave power at 2.45 GHz.

Both MS and FL (see Fig. 1) were fed with 220 V ac mains power. The consumed electric power in each case was measured by wattmeter W, (mod HP 6841 A) connected to the 220 V mains through the plug MP. A microwave network analyzer (not shown) was utilized to measure the attenuation of the microwave coaxial cable CC connecting MS to CA. This set-up enabled to measure the luminous flux of the lamp alternatively excited with 220 V ac or with microwaves, making   direct comparison between the two measurements without changing the lamp position inside the integrating sphere. To this end the precision of the measurements of the luminous flux (lm) furnished by DU was inessential.

A microwave leakage tester (Robin Electronics Limited, Norwich. UK, model TX90, not shown), featuring an 8 dipole analogue meter reading and having a power density accuracy of ±1dB, was used to measure stray microwave emission around the lamp. The relative errors of our measurements were always less than 10%.
Microwave lamp start-up was obtained, as usually, using a tesla coil tip in proximity of the tubes.

III.   RESULTS

The results obtained making direct comparison between the visible luminous fluxes produced feeding the lamp with microwave and with 220 V ac   are reported in Tab. I.

Tab. I. The ratio between the luminous emissions of the lamp (MW and 220 V) is reported in column 2 as a function of the microwave power applied to the lamp (column 1). In column 3 the electric efficiency of the MW method is reported.

MW power applied to the lamp (W)	Ratio between the measured luminous fluxes emitted exciting the lamp with microwave or 220 V ac	Electrical efficiency of microwave excitation η
3.7	0.69	0.045
6.3	0.77	0.07
8.5	0.86	0.09
11.2	0.90	0.11
15	0.94	0.14
20	0.95	0.15

The ac power consumed by the fluorescent lamp fed with 220 V ac resulted to be 14.8 W, as expected, in agreement with its data sheets. The measurements of the ac power consumed by MS as a function of the output power are reported in Fig 5.

These data demonstrate that when the lamp was fed with the same power, namely 15 W, the luminous fluxes were nearly the same, the flux emitted by the dipole driven lamp being a little bit smaller (94%) than the other. Furthermore, when the microwave output power was 15 W, the power consumed by the source MS was of 110 W, showing that the electrical efficiency of the microwave equipment utilized for visible light production was as low as η=14%. The graphic of Fig. 5 shows also that η increases when the emitted microwave power increases.

Stray microwave radiation emitted from the lamp was always smaller than 1 mw/cm^2 at 5 cm of distance. Accordingly no problem arose as far as safety was of concern. At the same time we could conclude that the feeding microwave power was nearly totally absorbed by the fluorescent bulb and transformed into light and heat, the wasted microwave power being ≤ 1 W when the output power was of 15 W.

While the luminosity of the commercial bulb increased during the first 80 s from the start up, using microwave power instead the heating time was of a few seconds. The microwave lamp was fairly dimmable.

Importantly, using the dipole antenna shown in Fig. 2 microwaves were nearly totally absorbed by the plasma discharge without the need of active or passive impedance matching devices.
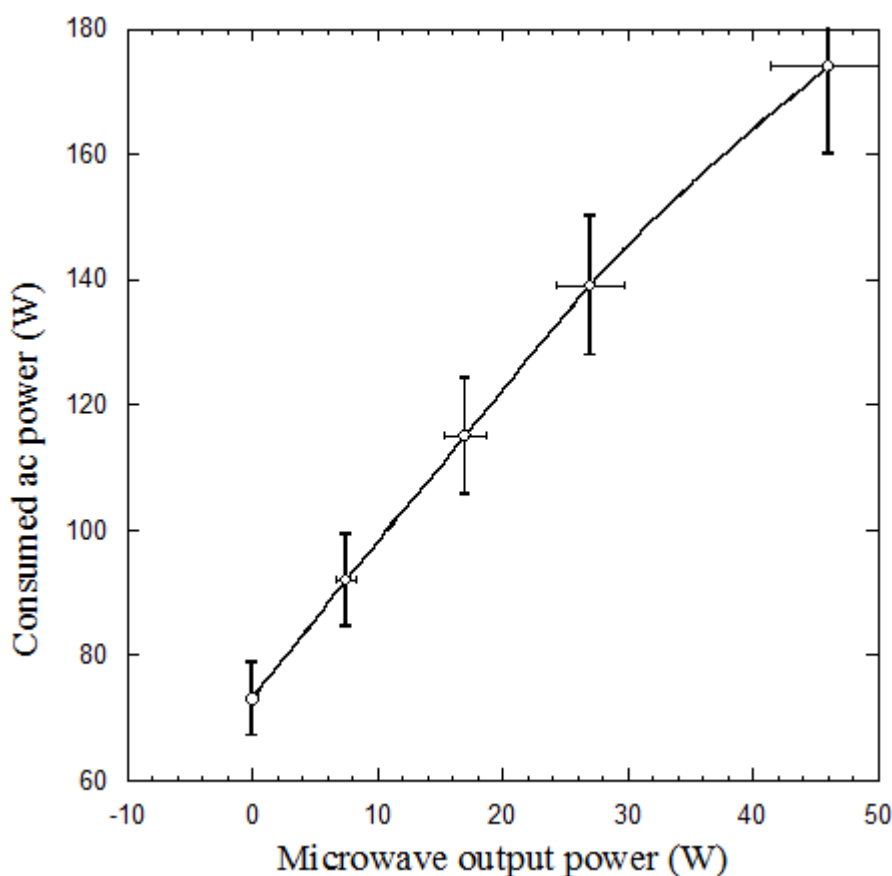

Fig. 5: Electric power consumed by the microwave source as a function of the output power.

We recorded the spectral emission of commercial fluorescent lamps of the same type of the lamp previously described, using the two excitation methods. The intensity of the emitted light as a function of wavelength in the visible region of the Sylvania lamp (mod. Mini Lynx Economy 15 W, 220 V/827) , as reported

in Fig. 6, resulted nearly the same, showing that for the development of a microwave lamp, as far as filling gases and phosphor coatings are of concern, one can rely on the available technology.
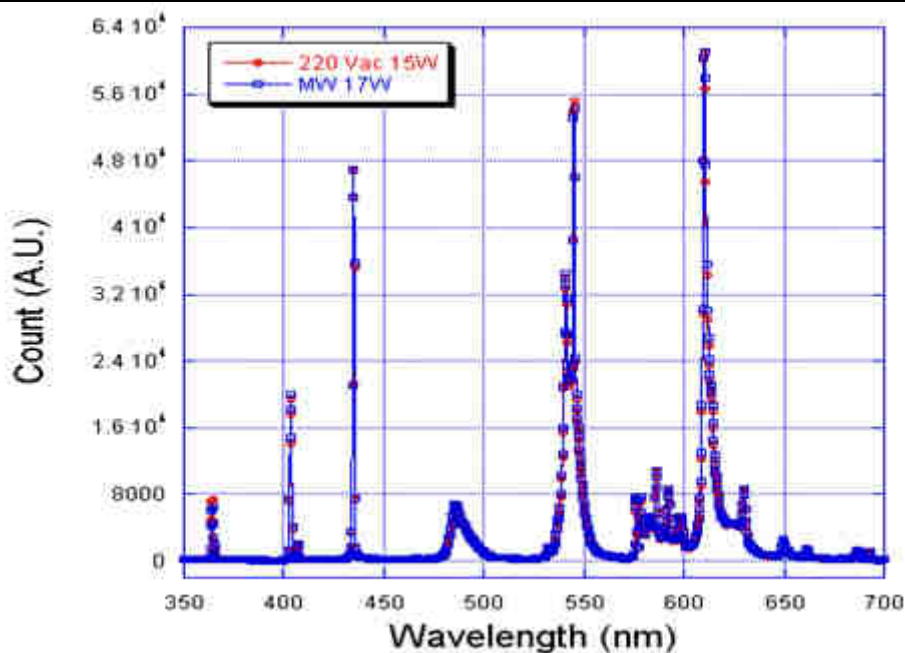
IV.   DISCUSSION

Aiming at assessing the validity of the novel method of excitation   we drove a commercial 15 W fluorescent lamp with its proper 220 V ac mains voltage and, alternatively, with microwave power at 2.45 GHz, making direct comparison between the emitted fluxes. To this end we utilized a dipole coaxial antenna placed along the lamp axis, just in the middle of its two U shaped emitting bulbs, in axial position. The luminous emission of the lamp placed near the center of an Ulbricht integrating sphere was measured in the two cases without moving the lamp inside the integrating sphere. The comparison of the measurements revealed useful and did not required to calibrate   the photometer head. The obtained results demonstrated that the microwave cavity-less fluorescent lamp is of simple design and can be excited using a coaxial dipole antenna.

The luminous flux obtained applying microwave power to a commercial bulb filled with a gaseous mix of noble gases and Hg vapors resulted to be of the same spectral content and   nearly of the same intensity of the one obtained with 220 V, the two feeding powers being equal to 15 W. Using microwave excitation the flux was 94 % of the one obtained with 220 V excitation. Considering that the bulb gaseous filling was optimized to produce a low frequency arc discharge, but not for a microwave plasma discharge, the result is encouraging.

Dealing with the possible advantages obtainable by developing a lamp based on this method of excitation, if luminous efficiency, bulb duration, costs and other industrial needs are at a premium, one must take into account a number of points.

a) Near field region

The plasma discharge inside the (fluorescent) bulb is sustained by the electromagnetic fields present in the near field region of the coaxial antenna and not by its radiating far field. The near field region is characterized by a high density of quasi-stationary microwave energy. The elementary theory of the short hertzian dipole antenna presented in standard texts of electromagnetism (Balanis, 2012) demonstrates that the peak electric field in the nearness of the antenna axis increases as r^{-2} and r^{-3}, r being the distance from the antenna axis. Accordingly the energy density of the dipole antenna increases as one approaches the antenna axis with a law of the type r^{-n}, n being in the range between 4 and 6. This type of law suggests that placing the antenna in a recess inside the bulb would give better results in terms of efficiency for plasma excitation. As a consequence when the lamp is fed with an external antenna, as in the present study, a more accurate selection of the glass tubing thickness and diameter, along with the number of tubes symmetrically placed around the antenna and of the antenna diameter itself will eventually give better results.

b) Electrical efficiency of the microwave source

The electrical efficiency of the magnetron source utilized in these preliminary experiments was rather low. The microwave source was a 100 W magnetron oscillator with an electrical efficiency of 14% at 15 W output power. However, it is well known that magnetrons of higher power and solid state amplifiers today on the market present a much greater electrical efficiency. Typically the energetic electric efficiency $\square$ of a magnetron emitting a few kW at 2.45 GHz is $\square$=0.71.

c) Gaseous filling

The accurate selection of gaseous filling of the bulb, in terms of gaseous components and of their partial pressures, is another important argument of investigation to optimize the luminous yield, since the mechanism of microwave plasma discharge is not the same of the ac (arc) discharge. Phosphors selection and use of mercury-less fillings, tentatively, may be other points to consider.

d) Temperature

The present study suggests that the externally placed driving dipole antenna can be utilized with advantage also in case of microwave excitation of high power bulbs, (in the power range, say, from 50 W to100 W at 2.45 GHz), since the all open proposed structure permits convective (passive) or forced air cooling with easy.

e) Long bulbs

The simple dipole antenna utilized in this study, fed with 15 W, is apt to excite a low pressure gaseous plasma discharges in a linear bulb of, say, 10 cm maximum length. Previous experiments performed at INO demonstrated that a coaxial leaky wave antennas (Kim, 1998), made out of a coaxial cable in which the external conductor is provided with a number of properly spaced radiating slots, can be utilized to excite a longer bulb, or a number of short lamps, passing through their recess. The picture in Fig. 6 shows four bulbs excited in our laboratory using a 20 cm long.leaky wave antenna passing through their recesses.
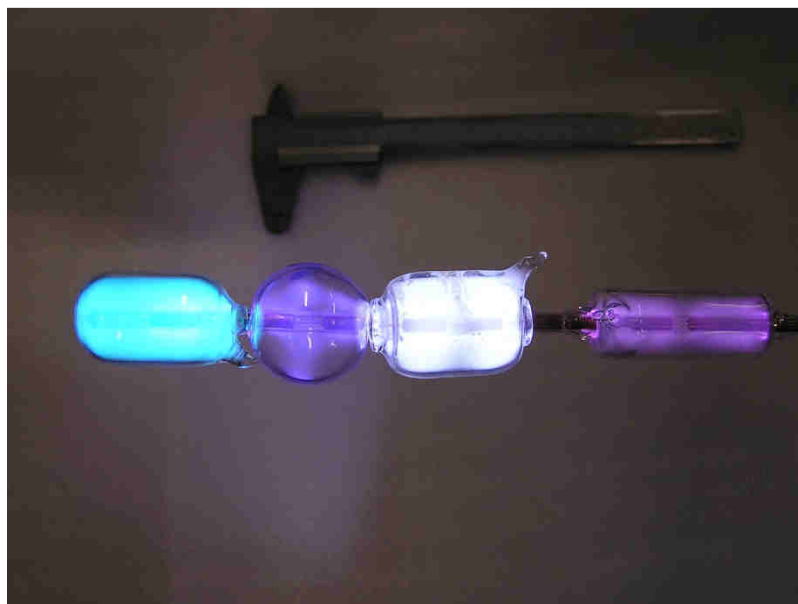

Fig. 6: The four lamps are simultaneously excited using a leaky wave coaxial antenna running into their bulb open recesses. From left to right: Cd lamp, XeBr excimer lamp, S vapors lamp, low pressure Hg UV lamp. The length of the lamp chain is about 20 cm. The applied microwave power is ≈ 50 W at 2.45 GHz, in continuous wave.

f) Bulb dispositions

To take advantage of the presence of the high density of microwave energy in the near field region of the antenna, in presence of rotational (axial) symmetry, the number of tubes of a fluorescent lamp and the diameter of the feeding antenna must be selected.

The scheme of Figure 7 shows the cross sections of two lamp composed, respectively, by three or by four tubes, excited by a central dipole.
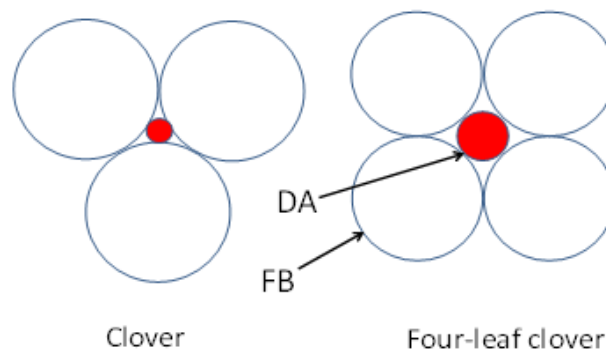

Fig. 7: Cross sections of a microwave driven fluorescent lamp featuring three bulbs (clover) and four bulbs (four-leaf clover) compact embodiments. FB: fluorescent bulb; DA: dipole antenna.

Observing the embodiments, from elementary geometry, one obtains that the ratio between bulb diameter and antenna diameter is ~9.1 (clover) and ~3.7 (four-leaf clover). In our experiments the diameter of the four tubes of the Sylvania lamp was 11.5 mm and the diameter of the coaxial cable antenna was 3.5 mm. To optimize energy transfer one ought to select four tubes of 12.5 mm of diameter (as the standard T4 fluorescent tubes) and a 3.35 mm diameter antenna. Using a leaky wave antenna we were able to excite efficiently four linear T4 tubes, (Philips, Master, mod PL-S 11W/827), in a four-leaf clover disposition. The four tubes configuration enables to construct a more powerful lamp without increasing bulb diameters, since in this configuration DA diameter is larger. Other configurations, also of different symmetries, can be envisaged, customizing the angular distributions of the emitted light.

V. CONCLUSIONS

This experimental investigation demonstrates that the method of excitation of a commercial fluorescent lamp using a dipole antenna placed outside the tubes is feasible, versatile and flexible. Further studies, though, are necessary to select suitable bulb geometries and/or gaseous fillings of the bulbs. The antenna can be placed in the nearness of the surface of one or more electrodeless fluorescent bulbs, with technical and practical advantages.

Microwave sources of high electric efficiency must be also selected to obtain advantages not only with bulb life span and bulb construction, but also with energy saving. The microwave power in the near field region of the coaxial antenna, providing very high electromagnetic energy density (presumably higher than a multi-mode or mono-mode applicator) is almost totally absorbed by the plasma produced inside the fluorescent bulb.

The microwave lamp unit in itself is very compact, showing times of a few seconds to reach its maximum light output and easy start up. In this way no problem should arise to fit it in every kind of industrial environment. The absence of electrodes permits dimming possibility and frequent switching, without causing early failures. The absence of ballast reduces costs, eliminating "buzz" and radio interferences.

Having no cavity, the proposed method is apart from the conventional definition and differentiation between multi-mode and mono-mode microwave applicators. The new method of activation candidates as a winner in lamp technology, starting from the construction modalities. It can be used in industrial and civil lighting plants and in multi-disciplinary applications. Long lamps, also having geometrical shapes very different from the linear one, can be excited as well using a leaky wave coaxial antenna.

Relevant advantages are attainable in comparison with other technologies. For instance the same stray microwaves emitted from the lamp can be utilized for motion-sensor applications, road monitoring, intruder alarms, etc.

Accordingly, the proposed technology can be useful to develop a microwave activated light source for large scale lighting applications.

ACKNOWLEDGEMENT

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