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Split energy delivery to material heating at RF and microwave frequencies

***Abstract**. Combining coherent sources can be advantageous in obtaining the desired distribution of electromagnetic fields to heat plasmas and other loads such as liquid chemicals. Split multichannel energy delivery was shown to allow for generating spatially symmetrical field patterns but has also brought new applications of the multiphase microwave or RF mains identical to those used at AC line frequencies. Several techniques of obtaining multiphase microwave sources have been discussed. They include multiphase sources, where forced synchronization is implied changing a number of independent power oscillators into a single and reliable multiphase power source. Examples of heating applications are provided for both the microwave and RF generator arrangements.*

***Streszczenie.** Sumowanie koherentnych źródeł mocy może być korzystne dla uzyskania określonych rozkładów pola potrzebnych do nagrzewaniu takich materiałów jak plazma lub ciekłe reagenty chemiczne. Wielokanałowe rozdzielenie mocy nie tylko umożliwiło generowanie symetrycznych rozkładów pola, lecz także zaowocowało nowymi aplikacjami wielofazowej sieci w.cz lub b.w.cz. identycznymi do tych znanych z sieci energetycznych 50/60 Hz. Przedyskutowano szereg sposobów aranżacji mikrofalowych sieci wielofazowych ze sztywną synchronizacja kilku oddzielnych oscylatorów mocy. Podano przykłady zastosowań tej nowej techniki zarówno w zakresie RF jak i częstotliwości mikrofalowych. (**Wielokanałowe dostarczanie energii przy nagrzewaniu materiałów w polach w.cz. i b.w.cz.**)*

Keywords: poly-phase RF& microwave generators, heating of liquids and plasma
Słowa kluczowe: wielofazowe generatory w.cz.i b.w.cz., nagrzewanie cieczy i plazmy

Introduction

One of the applications of RF or microwave energy is heating of different materials such as foods or chemicals. This application has become popular as most of the materials quickly become hot when exposed to high power RF or microwave fields. A very typical example of a microwave heating device is a microwave oven, which is equipped with multi-mode cavity energized from vacuum magnetron or transistor generator. Some microwave ovens have more than one source of power for cavity energizing. When more than one power source is applied, a more homogenous distribution of field can be obtained capable of delivering more even heating of the load than would be possible with a single power source. Field homogeneity can be enhanced with the use of field stirrers. However, in the well known professional-grade ovens from Panasonic no field stirrers have to be applied when microwave energy supply combines as many as 4 magnetrons. Industrial heating applicators often use the more generic rectangular or circular waveguide arrangements. If dimensions of the work-piece are small compared to the waveguide's cross-section, one can expect the heating to be performed over the whole load. Nevertheless, when conductivity of the material is too high, the wave tends to penetrate only a thin skin layer of the material exposed to the incident wave, which is propagated from the waveguide side the power generator is connected to. And only that wave-penetrated portion of the material can be well heated.

The heating process can be well observed visually when rectangular waveguide is used for generation of gas plasma crossing the waveguide inside the dielectric tube. It can be seen that the plasma gets hotter on the side the incident wave is propagating from. Usually, the problem of one-sided heating of plasma discharge can be eliminated by applying plasma gas flow in the form of a swirl, which helps make the plasma temperature distribution more homogenous. Note that no such homogenization will be possible if a similar one-sided heating would be applied to a solid sample. Therefore, it is self-evident that the improvement in plasma and non-plasma heating processes can be accomplished by importing a good symmetry of energy supply. Among the older but still good and currently used examples one can recall the construction of the plasma cavity known from [2] where a multi-point coupling of plasma column to microwave generator has been accomplished by means of multiple small coupling windows distributed symmetrically around the plasma axis. Plasma or any other fluid could therefore be heated as if it itself was focusing radial streams of energy (see Fig.1). Similar cavity has been applied in the reactor for microwave-assisted chemistry offered by CEM Corporation.

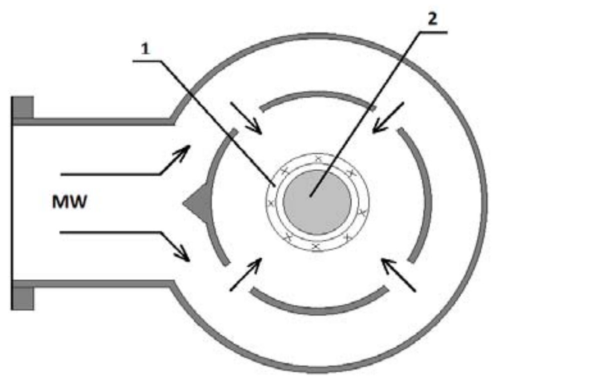

Fig.1 Plasma cavity with multipoint coupling [2], 1- quartz tube, 2- plasma or other fluids

Another approach to importing symmetry consists in a very careful design of resonant cavity, where all the non-symmetrical coupling elements should be kept far away from the plasma load. As suggested in [3], an appreciable symmetry of the field can be achieved using pure coaxial TEM modes, the coaxially symmetrical low impedance sections and other similar means described along with different designs of the MIP's (Microwave Induced Plasma) cavities. Symmetrical heating aimed at the division of energy into substantially equal portions and then transmitting those portions evenly onto each side of the discharge has also been discussed as a means of enabling generation of donut-shaped plasmas.

Methods

This paper is an attempt to extrapolate solutions applied to microwave plasmas reported in [3] to cases of non-plasma heating applications. Generalization of those results includes the heating of liquids and solid state samples and widens the frequency range to include the RF bands. This generalization also covers novel solutions suitable for generation of multi-phase RF and microwave power. Finally, it also utilizes the spatial combining technique known from [1].

Whatever the source of split energy, the plasma or any other loading material can be considered an energy summing element, an absorber, which receives portions of energy distributed around, changing all of them immediately into heat. For instance, the method of splitting energy into portions with further summing (absorbing) them into the load could be applied to obtain the almost pure H-mode heating at microwave frequencies. In microwave bands even a single turn of an inductor would be too long to enable generation of a solenoid-like field. In the solution proposed in [3] (see Fig.2) instead of full turns a number of partial turns has been introduced to form a short multi-helix, which was capable of exciting the H-type microwave discharges in argon gas. The energy split distributed between the helices was then combined symmetrically as the heat released in plasma column [3]. Application of that technique to non-plasma loads seems straightforward.

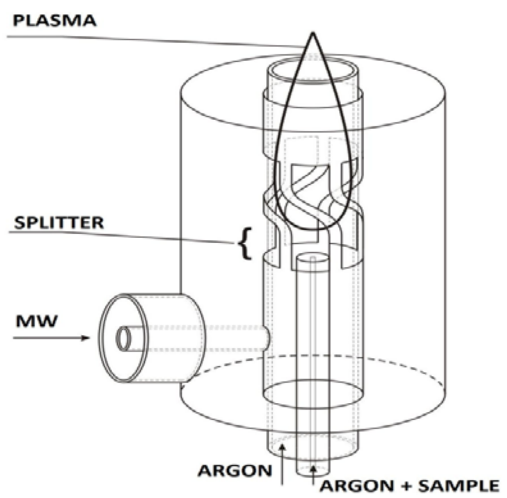

Fig.2. Multi-partial- turn H-type MW plasma applicator [3]

Generation of multi-candle discharges is yet another application of the split energy concept originally described in [3]. It is aimed at splitting the internal conductor of the coaxial line into several λ/4 long tips and burning up candle-like plasma at the end of each tip. The candle-like discharges situated very close to each other make a garland discharge behaving as one plasma work-piece, which consumed all of the propagated energy changing it into heat. One may notice that the latest two methods have much in common with the spatial combining technology known from literature [1]. Both use coherent energy portions and focus them in a certain place or region. In a lower frequency range, power amplifiers can be applied to help split energy supply arrangement as illustrated in Fig 9

Experimental

The multi-channel approaches described above may be extended to the scenario, where each participating channel in the combined heating of the load has different phase shift. As in the case of regular 3-phase power mains, thus organized RF or micro-waves can behave in a similar manner. For instance, discharge between three or more electrodes was shown to form hollow plasma disks, generally of polygonal shape [3]. That technique was originally used to heat helium plasma using three-phase rotating field and ca. 150W of power (see Fig.3).

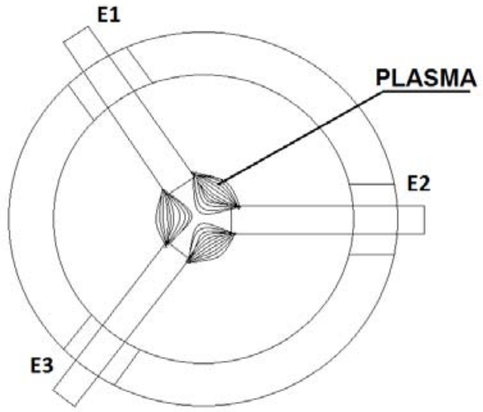

Fig.3. Three-phase microwave plasma device [3]

We have also experimentally examined the implementation of the same technique to heating other materials. Particularly the heating of liquids contained in a dielectric tube or inside open or closed vessels was of practical interest leading to the launch of a new family of microwave or RF –driven micro-reactors enabling appreciable acceleration of precise extractions, chemical syntheses etc.

Experiments were conducted with 15 mm o.d. and 9 cm tall quartz vessels placed at the axis of 45 mm i.d. stainless steel tube. The 2mm copper wire electrodes were connected in one plane to the N-female sockets mounted on the external wall of the tube. The electrodes terminated with disk-shaped plates were touching the quartz glass surface in the same plane (Fig.4). Four phase microwave field was obtained with the use of a splitter and appropriate phase shifts with progression of 90 deg have been obtained by means of unequal sections of regular RG-213 coaxial cable. A relatively good matching, swr<2, has been obtained with 10% water solutions of popular acids and alkali.

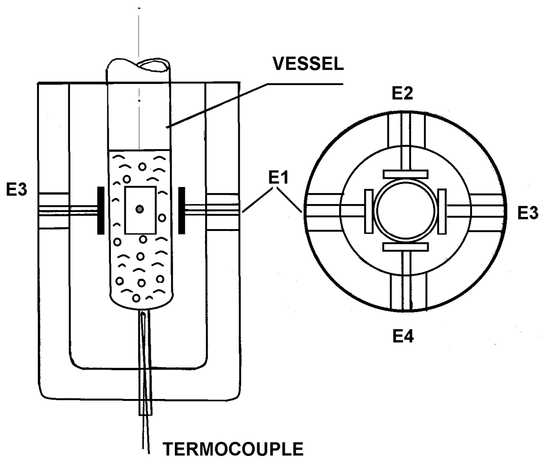

Fig.4. Application of rotating field assembly to supply a microwave driven micro-reactor

The use of multiphase supply in such micro-reactors was found advantageous as the longitudinal field component at the axis of every poly-phase system is vanishing. Therefore, one can place temperature sensors at the axis of the reactor without causing strong perturbations in electromagnetic field (see Fig.4). This means that no RF or microwave currents will be induced in the sensor shield, which will enable unperturbed temperature readings. As a result, one can avoid using non-contact thermometers, which are more expensive and less accurate than classical thermocouples. For pressure vessels, a hydraulic support may be incorporated enabling operating pressures in excess of 20MPa. Another micro-reactor is planned with the use of 3-electrode 3-phase cavity similar to that shown in Fig. 3, which will be adapted to enable the heating of much smaller samples placed in the con-shaped vessels with total volume less than 1 cm^2.

The energy split does not have to be aimed at division of high power microwaves delivered to the splitter from a single high power source. In the range of microwave and RF energies, the power energizing every one of the single helices present in the multi-helix arrangement of Fig.3 can be fed from separate, one per helix power amplifiers as illustrated in Fig.5. Thus, not only a homogenous heating of plasma and non plasma loads will be attained but also the possibility of increasing total operating power by combining powers from several sources. It is worth mentioning that, when applied to the well known RF driven ICP plasma, such an approach should lead to further reduction in plasma noise and to the improvement of detection limits of ICP spectrometers. Experimental results with the new ICP-MS spectrometer will be discussed in another publication. Thus far an analysis of multi-helix coupler has been described in [6].

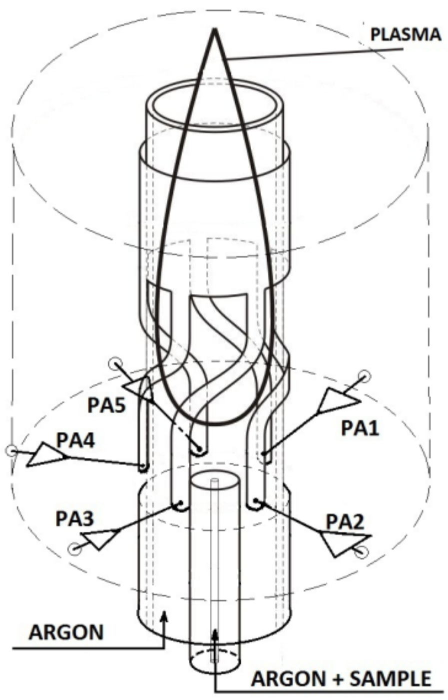

Fig.5. RF driven ICP source with plurality of amplifiers (more turns and symmetrical energizing would be advisable in practical RF device).

It is worth stressing that plurality of power sources can deliver total power much higher than a single source could ever do. And that can be achieved along with a possible reduction of the cost per kilowatt. However, when combining power sources, one should take into consideration that cross-coupling between generators should be small enough to prevent faults. Low cross-coupling can always be achieved when the work-piece size is large compared to the dimensions of a single power source coupling elements so that the attenuation of microwaves propagating along the work-piece is sufficiently high. Setting the magnetrons in an array, where distances between the antennae were uneven multiples of quarter wavelength, should also be mentioned as it has already become popular in construction of cheap microwave dryers. Decoupling between two microwave magnetrons can easily be achieved using a polarizer placed in a circular waveguide-based double launcher described by Puschner [4]. We have constructed a similar but more practical power combiner using a 76mm x76 mm square shaped waveguide (see Fig. 6).

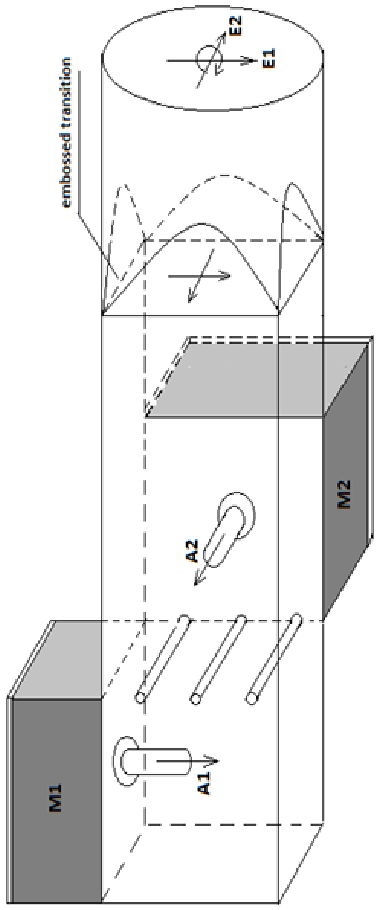

Fig.6. Combining powers of 2 magnetrons using a square-shaped waveguide

That efficient design was used for microwave-assisted nano-structuring of molten glass [5]. In this case, the polarizer has been placed inside the square–shaped waveguide section and antenna A_2 of a second magnetron at a distance of 3 cm from the polarizer rods. Unexpectedly, it appears that the magnetrons could have also been mutually synchronized to self-establish a 90 degrees phase shift between them. The poly-phase oscillations can be obtained by introducing quarter wave long sections as is shown in Fig. 7 for a 3-phase case. We tested that synchronization could have been achieved in a set of up to five magnetrons coupled together. When the synchronization is achieved, each of the magnetrons should “see” the load and the infinite input impedance of the inter-coupling sections of microwave lines, which behave as if they were virtually grounded in the middle point.

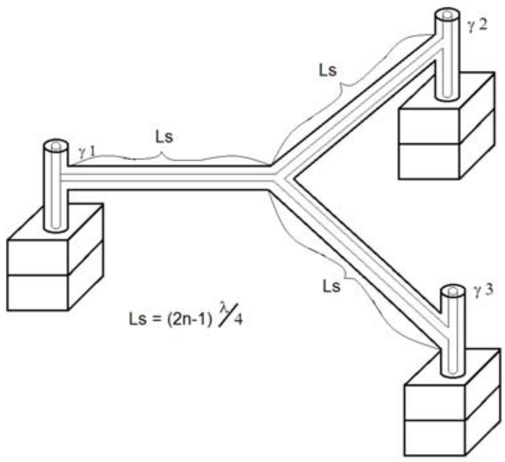

Fig.7. Synchronization of 3 magnetrons – an example

Such a virtual middle point ground should appear only when all of the star-connected magnetrons generate the desired multi-phase powers. With such synchronism the input impedances of the inter-coupling sections seen by each of the magnetrons are infinite. The inter-coupling between the magnetrons becomes stronger only for a short period until the synchronism is established.

Generation of multi-phase fields by plurality of oscillators and propagating those fields in waveguides is yet to receive theoretical description, which should take into consideration also the numerous telecommunication applications of the poly-phase idea.

As for heating applications, one can conclude that the multi-phase field propagating in waveguides can be utilized for heating of the co-axially shaped and circularly symmetrical loads or at least those behaving as if all of the components of rotating field can be equally attenuated. Otherwise, synchronization between the generators could be perturbed developing uncontrollable levels of reflected waves, which may lead to malfunction of magnetrons. The system with separate circulators shown in Fig 8 is of course more reliable, although more expensive. Such a system is currently being used in our laboratory.

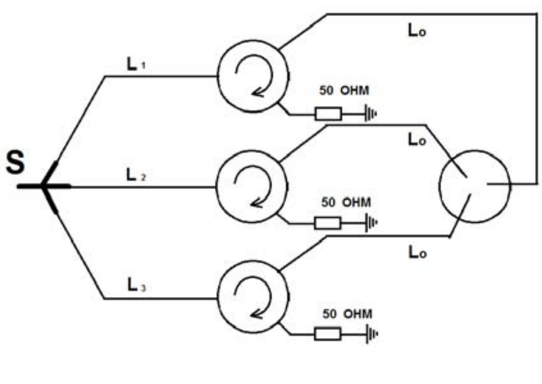

Fig.8.The use of microwave circulators in the multiphase system

At the lower frequency range, the multi-phase operation of plurality of power sources may be obtained with the use of power amplifiers, which are connected in the closed ring and each is fed from the predecessor throughout the phase shifting networks arranged from sections of screened cables and lumped capacitors as shown in Fig. 9.

One can also apply plurality of power amplifiers fed from a single power oscillator via different sections of coaxial cables each providing a predetermined phase shift. The power oscillator can be created from the same power amplifier equipped with a positive feedback circuit, which enables a class C power operation (see Fig.10).

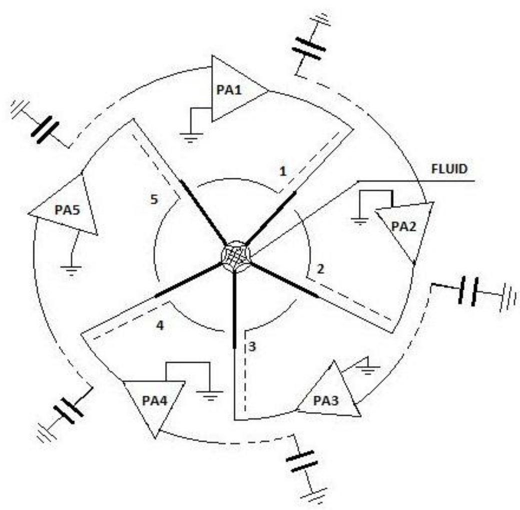

Fig.9. Power ring oscillator as a means of supply for a multiphase-energized load

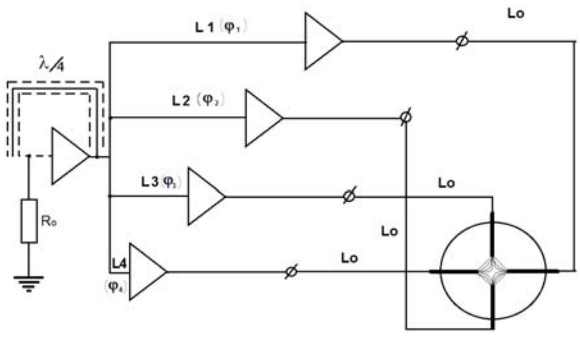

Fig.10. An idea of multiphase plasma excitation source built using power amplifiers

In our experiments, the regular CB radio KL-203-type 100W power amplifiers have been applied with twice the setting of quiescent current. Four sections of coaxial cables were used as phase shifting circuits. The frequency of operation was self established to ca. 12.30MHz.

Results and Discussion

Application of RF power and microwaves for the heating of different materials can be facilitated by dividing the energy into a number of coherent portions and delivering them to the load in order to guarantee given field distribution. Most significantly, axially symmetric field distribution favorable for heating the plasma and liquids can be composed by summing the energy of common (in-phase) and multi-phase fields. One of the purposes of this work is to shed more light onto the features and applications of the split energy concept. This concept was shown to be applicable for heating variety of materials including solid state and fluids such as plasma or wet chemicals. The heating may be performed in waveguides with rotating modes or in cavities with multi-point energy coupling. By applying the TEM mode propagating coupling elements one can compose the desired field distribution e.g. in order to attain good symmetry in heating. Split energy heating may be performed either by using the common phase design, in which the energy is spread between the portions of the load, or by using the poly-phase design, where heating can be focused on geometrically small objects such as plasma or micro-vessel reactors filled with reagents. The designers may choose a multi-helix coupler to excite the pure H-type coupling but at the beginning of the process, when conductivity of cold mixture of the reagents is low, the phase difference between the helices may be introduced in order to excite also the E-type coupling. Examples have been provided describing how to make equal portions of coherent energy using power dividers, phase shifters and ferrite circulators, as well as by applying synchronized oscillators consisting of magnetrons or RF amplifiers. Special attention has been paid to the applicability of multi-phase arrangements as a novel technique with the potential of finding a number of different applications.

Conclusions

A new approach to the heating of materials employing split energy concepts has been presented. Examples have been provided for plasma loads as well as for other types of heated matter such as liquid or solid state materials. Construction of split energy supply with arbitrary phase differences between channels has been described and the means of generating poly-phase power at microwave as well as RF frequencies have been illustrated by examples of the 3- and 4-phase devices. A new multi-helix coupler has been proposed, where the H-mode can be altered by introducing a controlled phase difference between the helices in order to enable E-type coupling. This may be advantageous when the load material strongly changes its conductivity and permeability during heating. The poly-phase energizing of chemical reactors whether of plasma or non-plasma types enables focusing the energy onto geometrically small loads and can thus be adapted as a dedicated technique in the construction of micro-reactors.

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