# Design and Evaluation of a Novel Spark-Plug Based on a Microwave Coaxial Resonator

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*Abstract* — **Innovative automotive engine concepts using direct gasoline injection demand for new ignition concepts. A novel spark-plug concept based on a microwave coaxial resonator is proposed, which generates a free-standing plasma flame. In this paper, design and realization of such a quarter-wave resonator at 2.45 GHz is presented and first experimental results are given showing the plasma-ignition properties of this resonator.**

## I. INTRODUCTION

In the last years, gasoline engines have been the subject of continuous improvements. Presently, the so-called spray-guided direct gasoline injection is considered as the upcoming engine concept, leading to a considerable reduction of fuel consumption and gas exhaust. In this concept, a gasoline spray is injected into the combustion chamber without moistening the walls of the chamber. During ignition the gasoline spray is surrounded by pure air, which has a positive influence on the thermodynamic processes and leads to the above-mentioned advantages. As the injected gasoline spray is not gasified but highly bundled it is difficult to be ignited. The ignition can only occur in the boundary of the spray, because only in this region the air-gasoline mixture is inflammable. Conventional spark plugs are not able to ignite such a gasoline spray reliably enough, because they provide only a small plasma arc, which, in addition, is very much shadowed towards the spray due to its electrode.

In this paper, a promising alternative approach is presented. It uses a microwave plasma and is based on a coaxial quarter-wave resonator, which allows to generate a plasma flame at the top of its inner conductor. This new structure is to replace the spark plug. It has a free-standing plasma flame, which can ignite the gasoline spray in a much larger region as the conventional system. The size of the resonator is scalable with the frequency and the duration of the plasma can be controlled by the microwave input signal.

## II. PRINCIPLE

What is needed to excite a plasma is a large microwave electric field, which is most easily generated by means of a high-Q resonant transformer. The coaxial quarter-wave resonator is well-known to allow generation of a plasma flame at the top of its inner conductor, if the field strength exceeds a certain threshold [1]. So-called plasma torches are based on this principle and have been examined in detail [2]-[4]. Those plasma sources are used for plasma chemistry and plasma surface treatment.

In contrast to [2]-[4], the resonator presented here also consists of a coaxial structure but is fed by a coaxial cable using galvanic coupling. Fig. 1 shows the structure on principle.

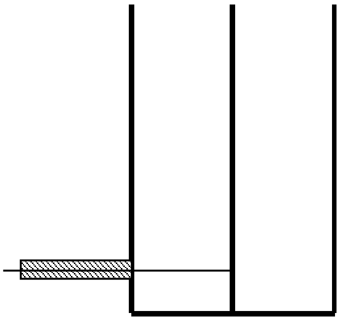

Fig. 1. Schematic drawing of the resonator with feeding line.

The following sections describe how such a resonator can be designed properly and show the parameters chosen for realization. Finally, experimental results will be presented.

## III. DESIGN CONSIDERATIONS

The length of the resonator scales with wavelength $\lambda$ and is determined to be $\lambda/4$. In the steady-state, one has a standing wave along the resonator, which has a voltage node at the bottom and a voltage maximum at the top. For the current the behavior is vice versa.

The distance from the bottom to the point where the feeding line is located (see Fig. 1) determines the input impedance. In order to minimize reflected power for the case without plasma, 50 $\Omega$ input impedance is realized. Hence, the resonator is ideally matched when connected to a 50 $\Omega$ power source.

Furthermore, the quality factor $Q$ is an important parameter. It describes the losses in the resonator and has to be maximized in order to obtain the highest E-field at the top of the resonator for a given input power. The basics how to achieve optimum $Q$ factor for a coaxial structure are given in [5]-[6]. Here, a resonator filled with air ($\varepsilon_r = 1$) is assumed.

The quality factor is defined as the ratio of maximum reactive power $P_{B,max}$ to the power $P_W$ consumed:

$$Q = \frac{P_{B,\max}}{P_W}. \tag{1}$$

The power $P_W$ is mainly determined by the power losses in resonator walls. They can be calculated according to [5] using the approach:

$$\frac{dP_W}{dz} = \frac{2\pi R_s}{Z_{F0}^2} \cdot \frac{1 + D/d}{D \cdot [\ln(D/d)]^2} \cdot U^2(z) \tag{2}$$

with

$$R_s = \sqrt{\frac{\mu_0 \omega}{2\kappa}}. \tag{3}$$

$D$ and $d$ denote the diameters of the outer and inner conductor, respectively, $R_s$ the surface resistance, which in turn depends on the angular frequency $\omega$ and on the conductivity $\kappa$ of the material. $Z_{F0}=(\mu_0/\varepsilon_0)^{1/2}$ is the free-space characteristic impedance. The function $U(z)$ describes the voltage along the resonator length $z$.

Assuming a sinusoidal voltage characteristic

$$U(z) = |U_{\max}| \cdot \sin\left(2\pi \frac{z}{\lambda}\right), \tag{4}$$

(2) can be integrated along the resonator length. This yields

$$P_W = \frac{\pi^2}{Z_{F0}^2} \cdot \frac{c_0\sqrt{\mu_0}}{4\sqrt{\pi \cdot \kappa \cdot f_R}} \cdot \frac{1 + D/d}{D \cdot [\ln(D/d)]^2} \cdot |U_{\max}|^2 . \tag{5}$$

The reactive power has its maximum value in case of resonance and can then be calculated as follows:

$$P_{B,\max} = \frac{1}{2} \cdot |U_{\max}|^2 \cdot B_{\mathrm{Res}}. \tag{6}$$

$B_{Res}$ is the susceptance in case of resonance, which is determined according to [6] as

$$B_{\mathrm{Res}} = \frac{\pi}{4} \cdot \frac{1}{Z_L}. \tag{7}$$

Here, $Z_L$ is the characteristic impedance of the resonator

$$\mathrm{Z_L} = \frac{\mathrm{Z_{F0}}}{2\pi} \cdot \ln\frac{\mathrm{D}}{\mathrm{d}}, \tag{8}$$

which finally yields the $Q$ value

$$Q = Z_{F0} \cdot \frac{\sqrt{\pi \cdot \kappa \cdot f_R}}{c_0\sqrt{\mu_0}} \cdot \frac{D \cdot \ln(D/d)}{1 + D/d}. \tag{9}$$

Fig. 2 shows the quality factor $Q$ for a resonator made of copper ($\kappa = 56$ MS/m) and a resonant frequency of $f_R = 2.45$ GHz according to (9).

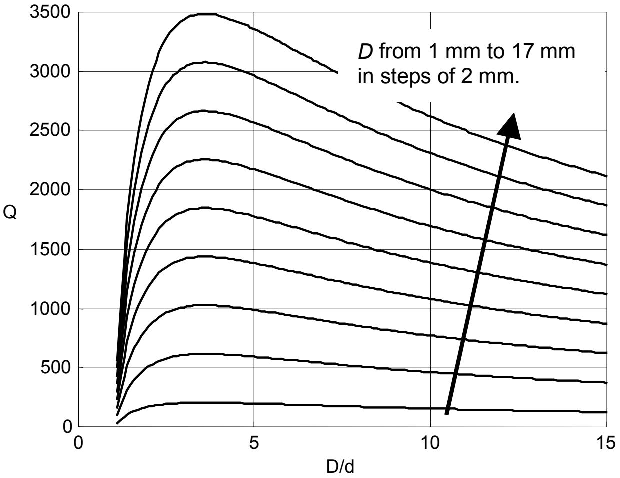

Fig. 2. Quality factor $Q$ versus diameter ratio $D/d$ with the diameter of the outer conductor $D$ as parameter.

Considering Fig. 2 the maximum of the quality factor occurs at $D/d = 3.6$ independently of the value of $D$. This is exactly the ratio at which a conventional coaxial transmission line has its minimum loss (see [6]).

The maximum electrical field strength, which occurs at the inner conductor, can be expressed as

$$E_{r,\max} = \frac{1}{d/2} \cdot \frac{|U_{\max}|}{\ln D/d}. \tag{10}$$

Inserting (6)-(10) in (1), a relationship between the input power and the maximum field strength is obtained:

$$P_W = \frac{1}{2 \cdot 4 \cdot 60 \cdot 120\pi\Omega} \cdot E_{r,\max}^2 \cdot D \cdot \left(\frac{1}{\left(D/d\right)^2} + \frac{1}{D/d}\right) \cdot \frac{\lambda}{4}\sqrt{\frac{\mu_0 \varepsilon_r \omega}{2\kappa}} \tag{11}$$

Fig. 3 visualizes (11) for a desired field strength of 18 kV/cm, which is according to former measurements (see also [7]) necessary for the generation of a microwave plasma.

One observes that there is no optimum. The larger the ratio $D/d$ the less power is needed. Hence, depending on the choice of the geometrical parameters it is necessary to find a reasonable compromise between the two parameters $Q$ and $E_{r,max}$. The dimensions chosen in our sample are described in the next section.

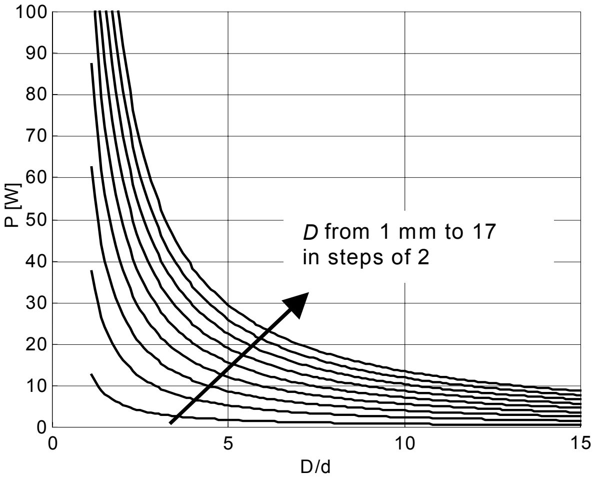

Fig. 3. Power $P$ necessary to reach a field strength of 18 kV/cm at the top of the resonator versus diameter ratio $D/d$ with the diameter of the outer conductor $D$ as parameter.

## IV. REALIZATION

According to the considerations presented in Sec. III, the geometrical parameters are chosen as follows: $D = 5.4$ mm, $d = 1.5$ mm, $L = 30.6$ mm, $Q_{theoretical} = 1100$ ($Q_{measured} = 800$), where $L$ denotes the length of the resonator.

The material of this first sample is copper, which provides a reasonable compromise between conductivity, melting point and ease of fabrication.

Fig. 4 shows the realized resonator in its package in comparison with a conventional spark-plug.

Fig. 4. Packaged resonator in comparison with a conventional spark-plug.

The chosen geometric parameters allow to reduce the thread diameter.

The absence of the ground electrode leads to an entire symmetrical free-standing plasma. Fig. 5 shows the top of the resonator with the plasma flame. The picture was taken through the window of a pressure chamber.

The measured quality factor of the realized resonator is approximately 27 % lower than the theoretical value. This is a result of the roughness of the surface and material impurities which in sum increase the loss.

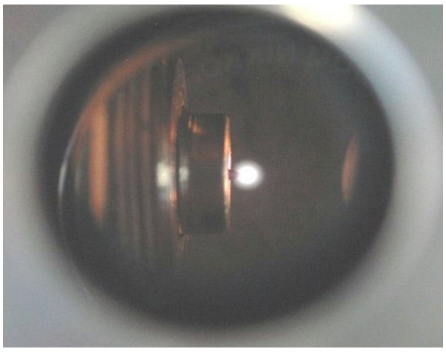

Fig. 5. Upper part of the resonator with a plasma flame on top of its inner conductor.

## V. MEASUREMENTS

### A. The measurement system

For an accurate evaluation of the resonator under realistic conditions a computer-controlled measurement setup was designed. The objective of the measurements is to determine the power necessary to guarantee the existence of a plasma flame. This is realized within a pressure range from 1 to 6 bar abs. to obtain also information about the pressure dependence of the power.

Therefore, the measurement system depicted in Fig. 6 was developed.

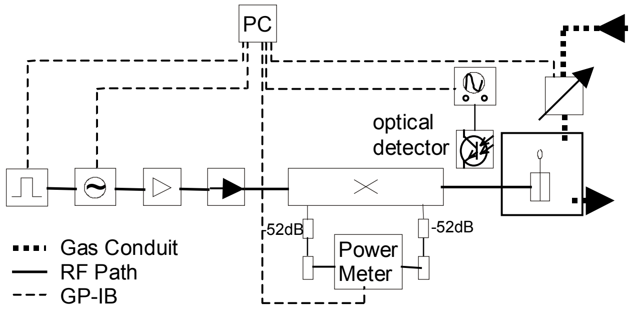

Fig. 6. Block diagram of the measurement system.

Pulsed microwave power up to 300 W is provided by a TWTA. The pulses are generated by the HP8116A function generator, which controls a R&S SME 03 signal generator connected to the TWTA. The output power path consists of an isolator followed by a directional coupler, which allows to measure the incident and the reflected pulse power using an Anritsu ML2408A power meter. At the end of this path, the power is coupled into the resonator. The latter is mounted into a pressure chamber that allows to vary the pressure. An optical sensor mounted at a window of the chamber is used as a detector for the plasma flame. The complete system including a pressure controller is computer-controlled via GP-IB.

### B. Measurement Results

In the following, first results are presented using the measurement setup as described above. As gases in the pressure chamber, argon and compressed air are applied. Fig. 7 shows the incident power required for plasma ignition versus pressure in comparison with values from [8].

The results show qualitative agreement with the results for microwave plasma generation published in [8], where the field strength necessary for plasma generation in argon and compressed air in a pressure range up to 130 mbar are presented. These values are extrapolated and the field strength is converted into power values using (11). Hence, the quantitative differences are probably a result of the very simple model used in (11), which for example neglects capacitive parasitics at the end of the inner conductor as well as losses in the feeding structure. In addition, differences in the experimental setups and the extrapolation of the data add uncertainties.

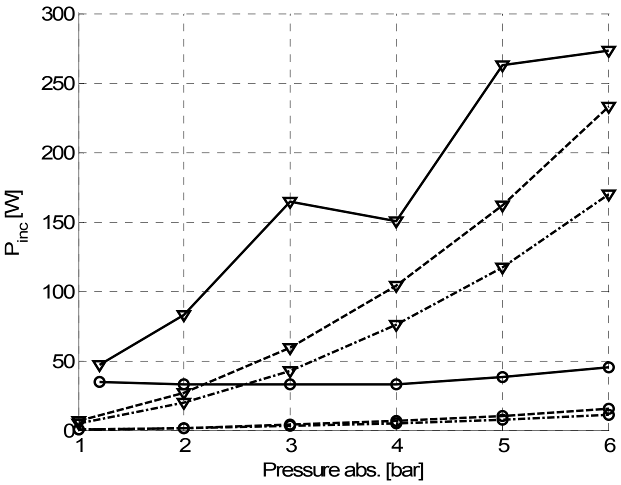

Fig. 7. Incident power necessary for plasma ignition in argon (markers: circles) and compressed air (markers: triangles) versus pressure. The solid lines are the measured results, the dashed and chain-dotted lines refer to measurements published in [8] for Q = 800 or Q = 1100, respectively.

Regarding applications in automotive engines, a pressure range up to 10 bar abs. has to be covered. This necessitates high power levels, which however have only to be applied for short times. The duration of these pulses and the repetition rate depend on the respective operating point of the engine. Hence, average powers of only several watts are required, which is comparable to the conventional spark plug.

## VI. CONCLUSION

A promising concept of a microwave-plasma spark plug using a quarter-wave resonator is presented. The design considerations for the resonator are given and a realization is described in detail. The systematic measurements in argon and compressed air in a pressure range from 1 to 6 bar abs. demonstrate proof of concept and are in agreement with experiments at lower pressures [8]. The free-standing plasma flame offers a high potential to be applied for spray-guided direct gasoline injection to reduce fuel consumption and exhaust gas emission.

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