Slotted Coaxial Line and Associated Measurement System for Determination of Dielectric Properties of Gas Plasma

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Abstract: The paper presents the development of a setup for measurement dielectric properties of ignited gases. It will further describe in detail the equipment and the design of necessary RF components calculated by using WIPL-D code. Experimental investigations emphasize the enhancement of measuring results by using a special waveguide filter.

1 Introduction

Industry benefits greatly from the application of plasmas. Apart from the semiconductor industry using plasma for special corrode processing it is further applied for treatment and work on materials. Many options are given to generate plasma usable in the industry. For instance DC discharge or capacitive ignition at low ISM bands are well known as the conventional ignition method. Great advantages can further be achieved by using microwave energy at 2.45 GHz for plasma ignition. Provided, that gas and plasma are surrounded by a quartz tube the microwave energy can be supplied in a contactless manner. Considering the fact, that the feeding components have no contact with the reactive plasma the life span of such plasma sources can be enhanced considerably in comparison to conventional sources. One drawback of the microwave feeding plasma source presents the change of dielectric properties and conductivity during the ignition process. It is therefore essential to ensure by design, that high electrical field strengths can be achieved in order to initiate the ionisation and ignite the gas filling. For calculation, the gas can be characterized by $\varepsilon_r = 1$ in the state before ignition. However, after ignition the gas appears as an electrical conductor. Hence, the microwave ignition mode can no longer be used for the system feeding. A second mode will be required. The idea of the implemented design consists of combining both modes without external switching to match the system to one microwave generator.

In this context the E_{010}/Coax- resonator is mentioned as one example for feeding the system. The quartz tube containing the gas is arranged in a resonator axis. Before ignition the feeding system operates as E_{010} mode resonator [1], influence of quartz tube and gas can be neglected for this purpose. Good electrical conductor properties can be achieved with high field strength initiating the ionisation of the gas. With a proper design the system operates as coaxial resonator after ignition. Profound knowledge of dielectric properties of the ignited gas is essential before designing the feeding system. A slotted coaxial measurement line is applied to ascertain the dielectrical properties of gas plasma.

2 Concept of the coaxial plasma measurement line

The following illustration depicts the design of the coaxial plasma measurement line and its components. The signal at entry port (1) is provided by microwave generator, whose power at 2.45 GHz can be adjusted between 0.3 kW and 3kW. To prevent backward reflections of the generator a circulator including water load (2) is placed in the line. A directional coupler (3) allows measuring of both, forward and backward reflected microwave power. By use of a coaxial measuring line and a horizontal arrangement a special waveguide to coax transition (4) comes into use. A mode filter consisting of a simple coaxial line (5) placed at the end of the waveguide coax transition is used to suppress generation of undesired modes in the subsequent measurement section. In view of intended applications the inner plasma conductor of the measurement line had to be constructed with a diameter of 30 mm. To obtain a 50 Ohm line the outer conductor should have 70 mm in diameter. For given dimensions particular attention should be paid to suppress generation and propagation of parasitic non-TEM coaxial modes. The matching of the cross sections between first filter (5) and the measuring line can be carried out by a conical line (6).

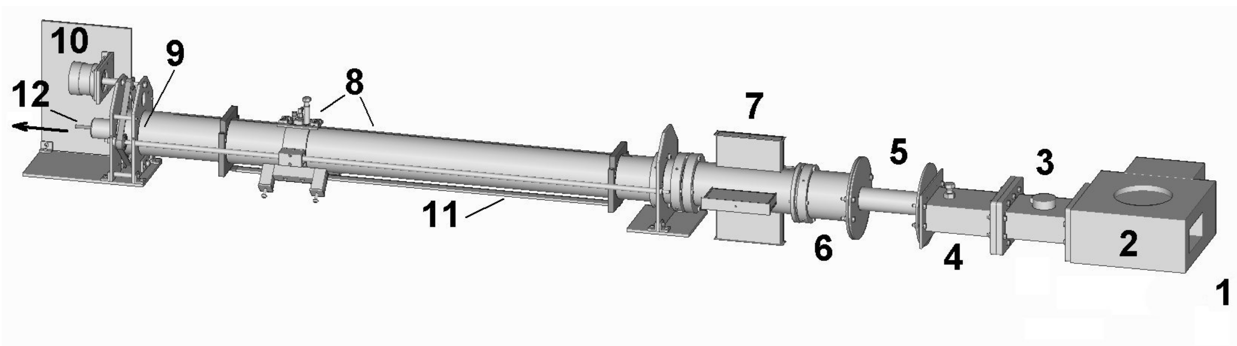


Fig. 2-1: Components of the plasma measuring plant:
Entry port (from Microwave generator) (1), circulator (2), directional coupler (3), axial coax-waveguide transition (4), first filter (5), conical line (6), second filter (7), slotted line with sled (8), short (9), step driver (10), length control (11), quartz glass and gas mixture arrangement (12)

The quartz glass functions as inner conductor of the measurement line. One end of the glass is placed in the end of the conical line inner conductor. The electrical connection between conical line and plasma is achieved by capacitive coupling. Radial asymmetries of the arrangement, the conus line itself as well as the transition between conical line inner conductor and the plasma line can generate a H_{11} parasitic mode. Considering the fact, that this mode has a guided wavelength approximately twice the one of the TEM mode, superposition of both would result in severe distortion of the measurement. Under the given circumstances the analysis of the probed data would be impossible. To minimize the parasitic mode along the measurement line, a second filter (7) is designed. It is one of the most important parts of the line. The actual measure line consists of a plasma inner conductor coated by quartz glass. This glass has a diameter of 30 mm and a thickness of 2 mm. A pump (12) used for producing a vacuum inside the quartz glass allows a special mixture pressured inert gas to be inserted into the tube. The outer conductor of the measurement line has a 70 mm diameter and is slotted at one side. A sled can be moved along the measuring line (8). The sled is equipped with a mounted probe reaching into the slot. A capacitive backshort (9) forms the end of the measurement line.
The measurement procedure works automatically controlled by a computer. By storing the measured data along the line a complicated numerical calculation is necessary to describe the dielectric properties of the plasma depending on the kind of gas, the gas pressure and the microwave power. This calculation produces only reasonable values if all parasitic modes are reduced.

3 Investigation of Measurement line components using WIPL-D Code

Axial coaxial-to-waveguide transition

The source section consists of magnetron, circulator and directional coupler for R26 waveguides. Due to the horizontal arrangement of the measurement line, an axial coax-to-waveguide transition is required. The transition is designed using WIPL-D code [2]. Figure 3-1a depicts the calculation layout.

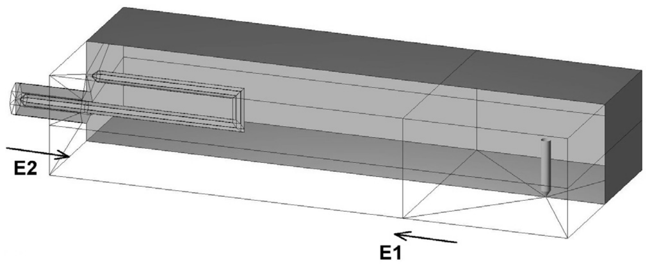


Fig. 3-1a: Calculation layout of the axial coax-to-waveguide transition

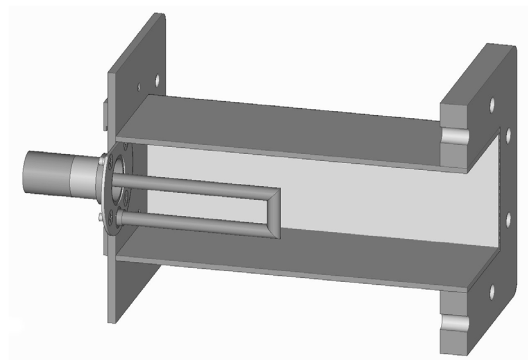


Fig. 3-1b: CAD layout of the axial coax-to-waveguide transition

A cut of the CAD layout is shown in figure 3-1b. The layout corresponds to the calculated data of the axial coax-waveguide transition. The influence of the feeding network was eliminated by using option "Deembedding S-parameters". The generation of the waveport ends at the plane E1, the TEM mode will be generated up to plane E2. The full wave loop implemented in the waveguide is coupling both, the electric and the magnetic field [3]. The figure 3-2 shows the calculated magnitude of S-parameters.

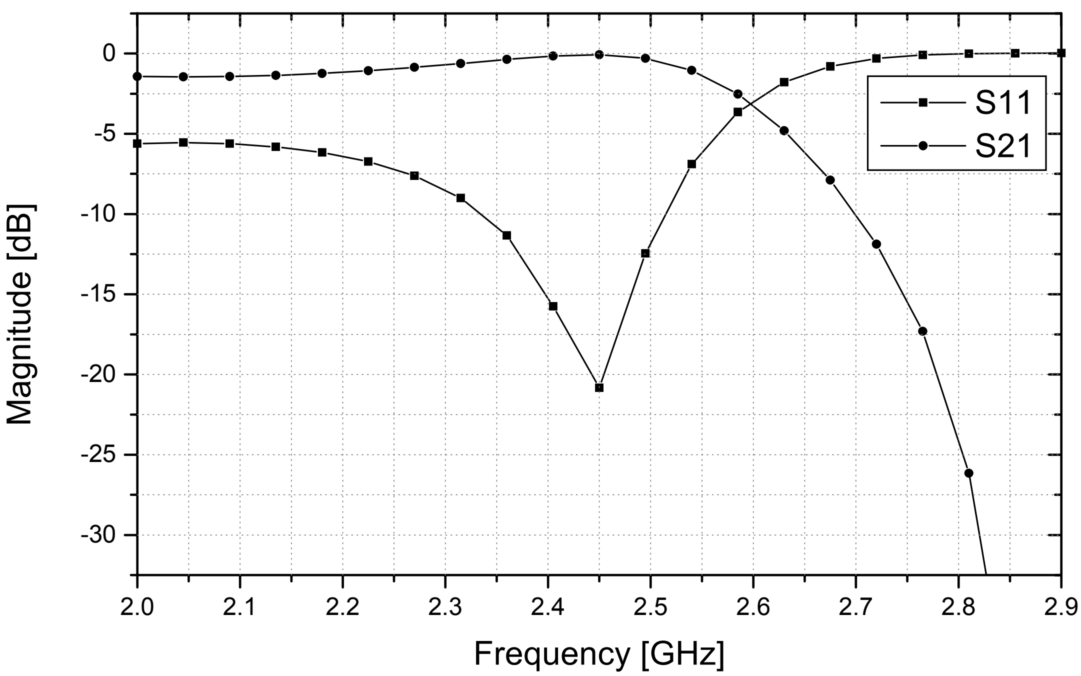


Fig. 3-2: Calculated magnitude of parameters s11 and s21

Conical line

The different coaxial diameters of the axial coax-to-waveguide transition and the measurement line can be matched to each other by a conical line. A ceramic ring is introduced to keep inner conductor in coaxial position with outer conductor. An exact centre position of the measurement line inner conductor is necessary in order to reduce the generation of the H_{11} disturbance mode. The ceramic support has a real part of permittivity $\varepsilon_r = 6$. The conical line matches both the outer conductors from 32 mm to 70 mm as well as both inner conductors from 14 mm to 30 mm considering the influence of the ceramic support. The influence of the feeding network was eliminated by using option "De-embedding S-parameters". The figure 3-3a illustrates the calculation layout. A cut of the CAD model of the constructed conical line is shown in figure 3-3b.

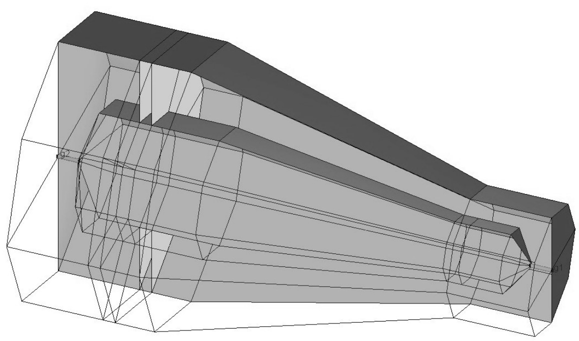


Fig. 3-3a: Calculation layout of the conical line

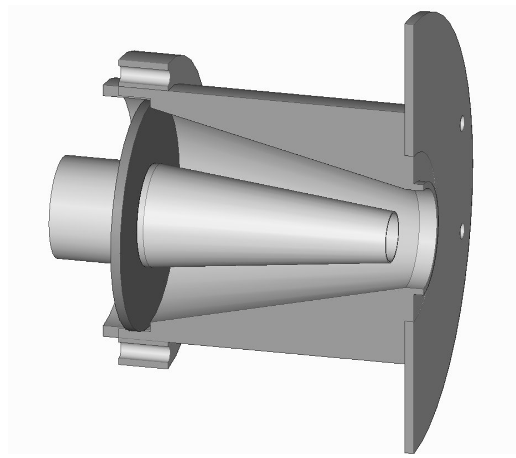


Fig. 3-3b: CAD layout of the conical line

The conical line was optimized for low reflection and small losses. The results are shown in figure 3-4.

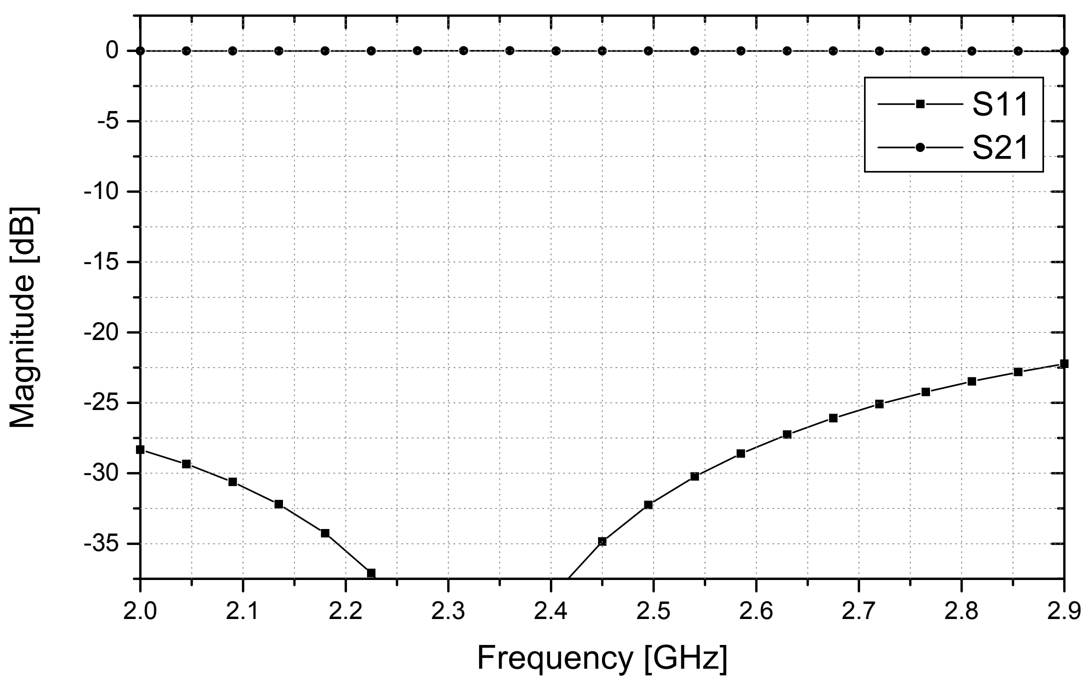
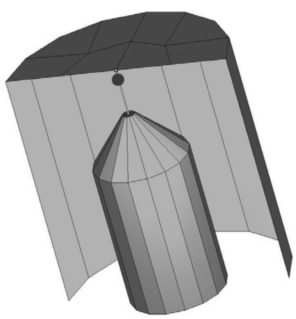


Fig. 3-4: Calculated matching and transmission loss

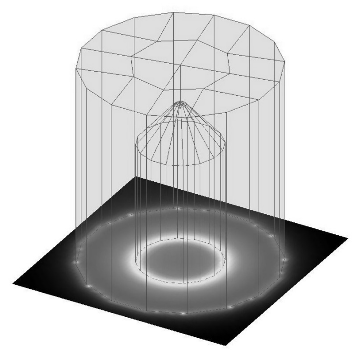
The electric field between the inner and outer conductor of the conical line is similar to a spherical wave having a center at the position of intersection of both points of cones [4]. Bent field lines and tolerances of the transition between conical line inner conductor and the quartz tube can generate the H_{11} mode.

Second Mode Filter

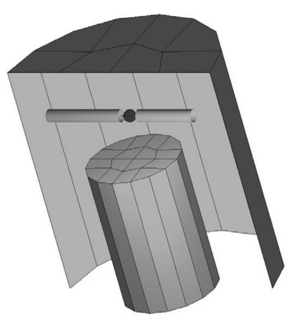
One end of the quarz tube is inserted at the thicker end of the conical line inner conductor. Corresponding to previous explanations the parasitic mode H_{11} can propagate in the measurement line. To prevent this propagation a second special filter (7) was designed and positioned directly at the input of the measurement line. Purpose of the filter is to transmit TEM mode, while blocking H_{11} mode. The Deembed option is used to subtract the influence of the generator feeding network. A simple direct wire connection at the inner conductor is used to generate the TEM mode. The generation of the H_{11} mode can be achieved in different ways. Most methods use two different generators having opposite phases. The combination of both generators to one feed and use of Deembed option of WIPL-D is impossible by the program up to this time. By placing a thick dipol above the coaxial line open end, the H_{11} mode can be generated by one generator only. Under these circumstances the Deembed function can be used for both mode generations. The figure 3-5 shows the kinds of generation and the electrical field distributions.



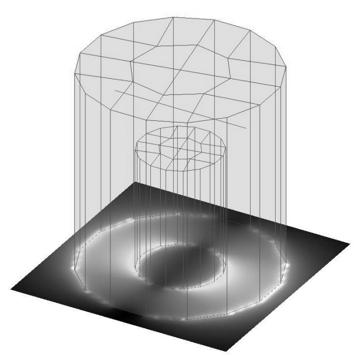
Calculation layout of the TEM generation



Field distribution using TEM generation



Calculation layout of the H_{11} generation



Field distribution using H_{11} generation

Fig. 3-5: Generation of the coaxial TEM and the H_{11} Mode

The effect of the filter is based on the interruption of the outer conductor surface currents of the H_{11} mode. At the inner side of the outer conductor of the coaxial cable, a surface current is circulating perpendicularly to the propagation direction of the microwave energy. By using rectangular hollow waveguides as stub lines, the mentioned current can be interrupted and the H_{11} mode will be reflected. The stub line consists of a quarter wavelength H_{10} mode hollow waveguide. As the H_{11} Mode consists of two current maxima and two minima across the section, four stub lines are required. If only two stub lines are used, the H_{11} mode rotates allowing the current minima to be placed at the stub line. In this case the stub lines would have no effect. The figures 3-6a-b show the calculation layouts of the filter for both kinds of generation. The figure 3-6c shows the CAD layout.

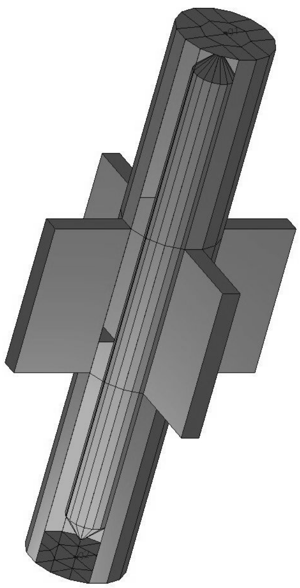


Fig. 3-6a: Calculation layout of the filter generated by TEM mode

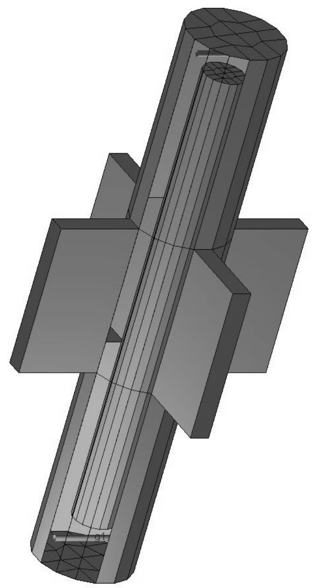


Fig. 3-6b: Calculation layout of the filter generated by H_{11} mode, dipoles at the ends of line

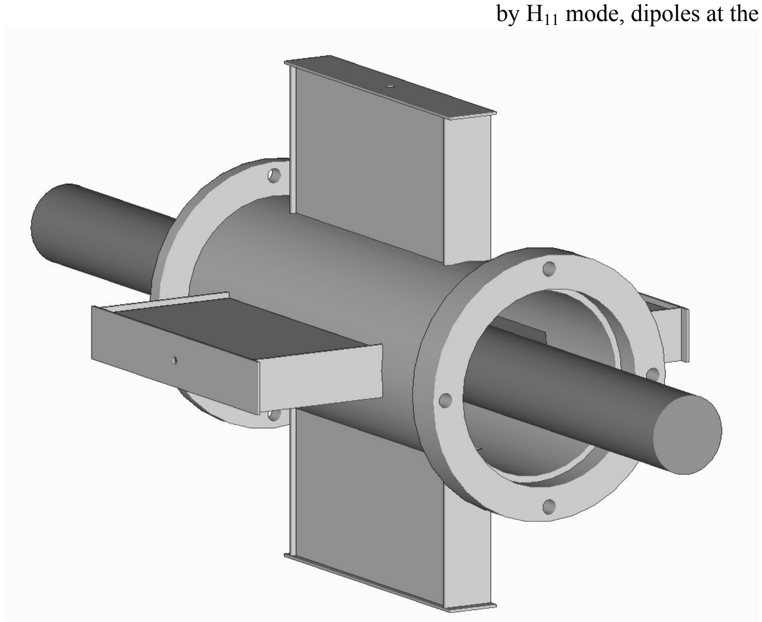


Fig. 3-6c: Realized Filter

The optimization process of the filter focuses on matching and on minimum or maximum transmission attenuation for the modes. Due to the fact, that the waveguide line stubs interrupt the coax outer conductor, the waveguide resistance for TEM mode in this area will change as well. The optimisation process has to consider both layouts. The calculated geometries after optimization of the TEM mode generation are the starting point of the second optimization by using the H_{11} mode generation. Further by using this data an optimisation for the TEM mode will be repeated. Subsequently, with a small number of iterations, good results can be found for both kinds of feeds. The figure 3-7 illustrates calculated S-parameters for the different types.

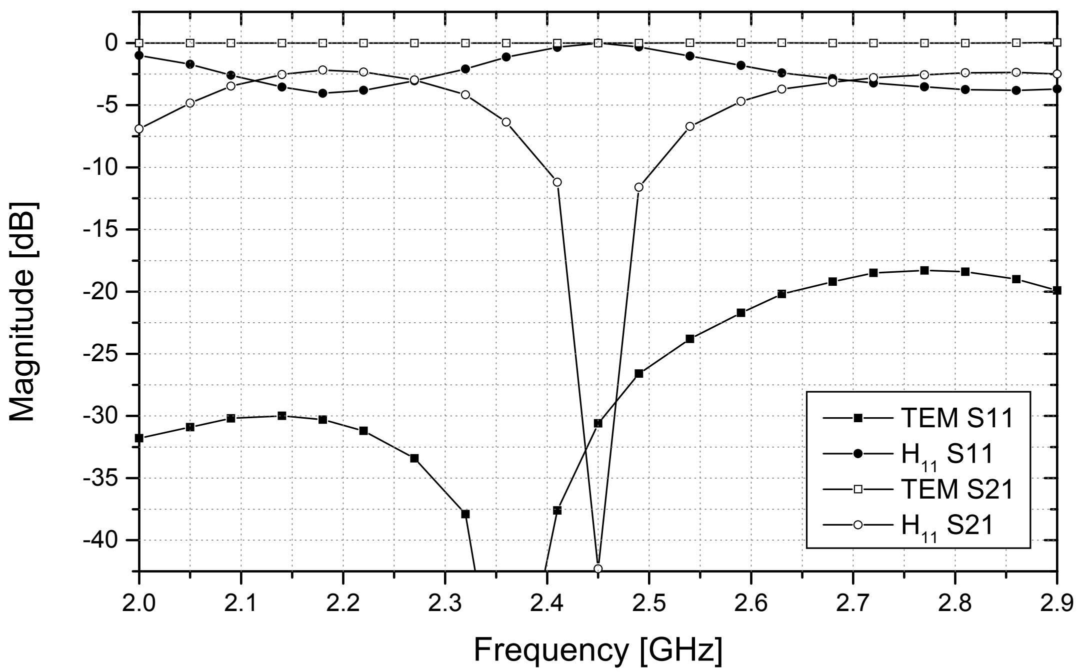


Fig. 3-7: Calculated S-parameters for TEM and H_{11} Mode

Figure 3-7 clearly demonstrates that the second filter transmits the TEM mode nearly without losses and having return loss of better 30 dB, while the H_{11} mode could be suppressed by 40 dB at 2.45 GHz.

4 Experimental results

The Wipl-D calculated components have no standard port expected for the R26 waveguide flange. The components are designed to be connected to each other, but adaptors are necessary for characterisation by means of a network analyser. In this way the electrical properties of the additional components will be included in the measurement of the components under test. The quality of the realized RF components can be described during the operating process. The constructed measurement line can be operated with or without the mentioned second filter. If the inner conductor of the measurement line consists of an ignited gas surrounded by quartz glass the shorted measurement line generates a standing wave, the average of which has a monotonous slope, positive towards the generator. The back reflected wave passing the circulator is terminated and dissipated in a water load. The standing wave on the measurement line consists of only one forward and one backward travelling wave. The probing starts from a position near the short and extends towards the generator. Figure 4-1 demonstrates the results of the scan with and without incorporated mode filter.

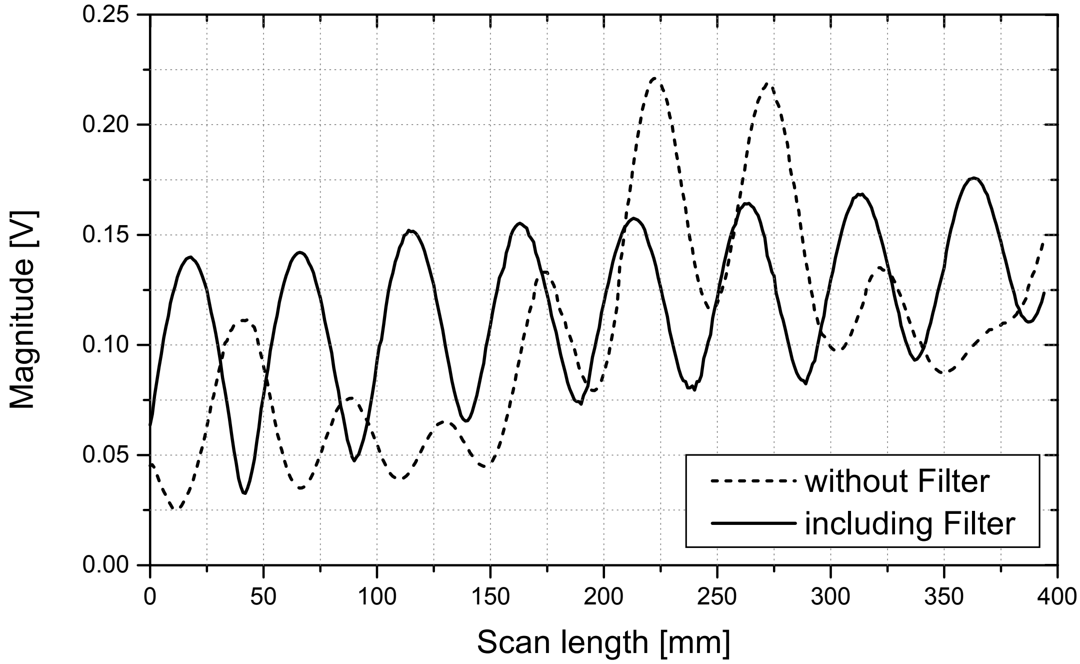


Fig. 4-1: Measured voltage proportional to the electrical field distribution, Ne 5 mbar, 400W at 2.45 GHz

The measured data in figure 4-1 show clearly the superposition of the TEM mode and the H_{11} mode. This superposition leads to an inhomogeneous distribution resulting in no clear attenuation along the measurement line of this length. On the other hand, the single TEM mode doesn't have a constant attenuation along the line. The reason for this fact can be found in the non-linear transmission parameter of the line due to the presence of plasma. A different ionisation of the gas results in a different conductivity of the inner conductor of the measurement line. It is therefore underlined, that any presence of H_{11} mode would significantly complicate the extraction the local complex dielectric constant. Therefore the second filter presents the major support component of this measurement line.

5 Conclusion

The presented paper described an arrangement for the determination of dielectric properties of the ignited gas by means of microwave energy. The major system components were calculated by using the WIPL-D code. They include an axial coax-to-waveguide transition, a conical line including a ceramic support and, as major part, a specially designed mode filter. The comparison between measurement with and without mode filter reveals the necessity and efficiency of the designed components.

6 References

[1] Meinke, M.; Grundlach, F.W.: Taschenbuch der Hochfrequenztechnik. Berlin: Springer Verlag 1956.

[2] WIPL-D Pro: 3D electromagnetic solver, v6.1, WIPL-D, d.o.o. Belgrade: 2006.

[3] Reich, J.; Ordung, F.; Krauss, L.; Skalnik, G.: Microwave Theory and Techniques. New York: D.Van Nostrand Company Inc. 1953.

[4] Meinke, M.; Grundlach, F.W.: Taschenbuch der Hochfrequenztechnik. Berlin: Springer Verlag 1992.