The Potential of RF Energy for the Ignition of Microplasmas

By Klaus Werner, Prof. H. Heuermann, and Dr. A. Sadeghfam

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Introduction

The emergence of radio-frequency energy as a heat source in many new applications is becoming a reality, enabled by a new generation of high-efficiency and high-power transistors. Klaus Werner, Program Manager at NXP Semiconductors, in conjunction with Prof. H. Heuermann and Dr. A. Sadeghfam at Heuermann Hochfrequenztechnik (HHF), uses the example of an innovative prototype 200W microwave power generator that drives microplasmas with the potential to enable highly efficient next-generation car engines … and also makes a spark plug sing!

There is a strong and increasing interest in the potential offered by radio-frequency-signal generated energy as a clean, efficient and well-controlled heat source for a myriad of uses, especially in industrial, scientific and medical (ISM) applications. Over the past 10 years, efforts to harness the possibilities of RF energy have meant the reuse of power transistors designed for use in telecom base stations. However, these devices have proved to be sub-optimal for ISM applications. The emergence of new high-efficiency high-power transistors based on silicon LDMOS technology and operating at the 2.45 GHz worldwide ISM frequency band is now energizing this technology. One particular application that could prove to be highly attractive is the solid-state RF/microwave heating of microplasmas, especially in the automotive and RF plasma lighting sectors.

Microplasma Ignition and Sustained Control

Recent years have seen growing awareness of the potential of microplasma, which essentially is plasma of dimensions on the millimeter or micrometer scale and which is generally characterized via operation under normal atmospheric pressure conditions. Dating back as far as 2005, research papers have been published on the ignition of plasma using distributed elements based on microstrip or coaxial structures at frequencies as high as 2.45 GHz.

The Department of High Frequency Technologies at the Aachen University of Applied Sciences is one body that has played a leading role over the past few years into the research of microplasma ignition at 2.45 GHz for various applications including spark plugs, plasma beams, and low- and high-pressure discharge lamps. The department's research has been largely based on an innovative impedance transformer achieving both the ignition and sustained operation of microwave plasma. It is based on a three-stage transformer network[1] (shown in Figure 1) that enables a frequency offset as small as 40 MHz between two states operating in the 2.45 GHz ISM band. This concept is known as bi-static-matching.

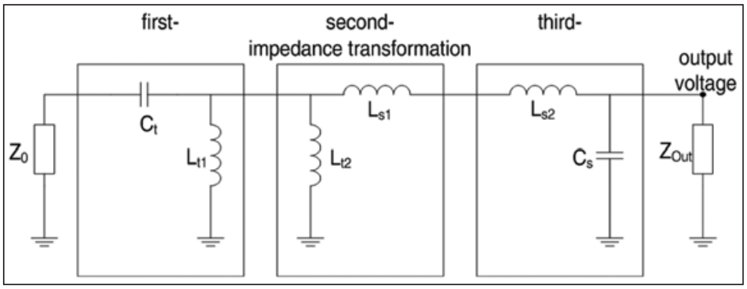

Figure 1 • Simplified electrical circuit of a three-staged impedance transformer network used to ignite microplasma.

Figure 2 • Microplasma driven by a 200W S11-locked microwave power generator.

Heuermann Hochfrequenztechnik (HHF), a company spun out of the Aachen University of Applied Sciences, has developed a special generator aimed at these plasma applications, and particularly for the operation of plasma beams or jets. As an example, a 2.45 GHz plasma jet with argon as its process gas that can either cut or weld materials at a temperature of greater than 3400°C, is shown in Figure 2.

However, this generator is also highly suitable for the operation of a microwave heating process offering microwave power up to 200 W. The generator's integrated control electronics obtains the best matching point in the 2.45 GHz ISM band, achiving stable operation and maximum efficiency at all power levels.

S11-Locked Microwave Power Generator

A microwave source producing a 2.45 GHz signal is essential for ignition and sustained operation of microwave plasma. To monitor the matching of the plasma during operation, a scalar network analyzer (SNA) is implemented in the generator (shown in Figure 3), which performs S-parameter measurements.

Figure 3 • SNA-based 200 W S11-locked microwave power generator from HHF.

The generator monitors load matching, irrespective of the presence of plasma. Sweeping the input signal over frequency enables a good indication of impedance matching of the microwave plasma over frequency. The frequency with the best match is identified and locked into the automatic control feature, thereby enabling ideal operational conditions. A block diagram of the SNA-generator is shown in figure 4.

The SNA-based generator includes: measurement channels for the incident and the reflected waves; a low-loss power isolator at the output; and various supplementary control and display electronic components. Figure 4 illustrates the basic workflow of the control electronics. Based on the S-parameter (S11) information of the detectors, a specially developed algorithm finds the best matching point in the frequency band and regulates the VCO (Voltage Controlled Oscillator); the output power is adjusted using a variable voltage attenuator. All units of the block diagram in figure 4 are implemented in a single module, shown in figure 5.

The electronics for low power and signal processing are implemented on the green PCBs (top left and center of the module in Figure 5). The module's preamplifier (top right section of the module in Figure 5), which delivers an output power of 20W, has been shrunk by the

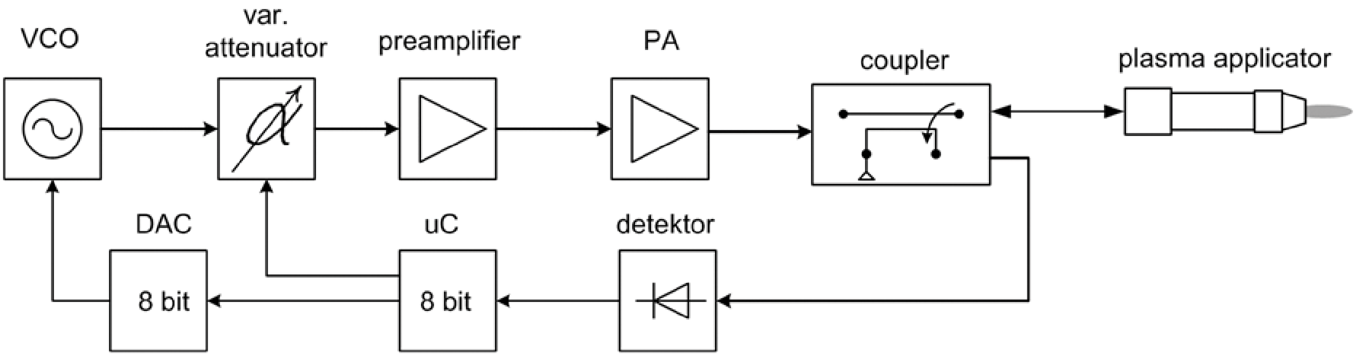

Figure 4 • Simplified block diagram of the SNA-based S11-locked microwave power generator.

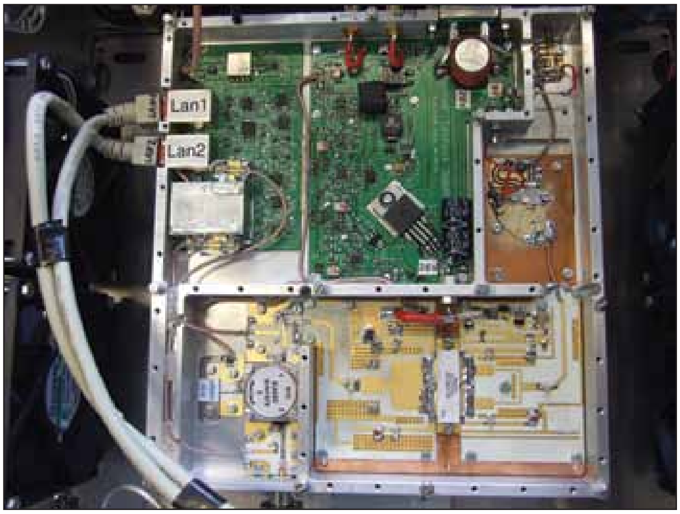

Figure 5 • The internal module of the SNA-based S11-locked microwave power generator.

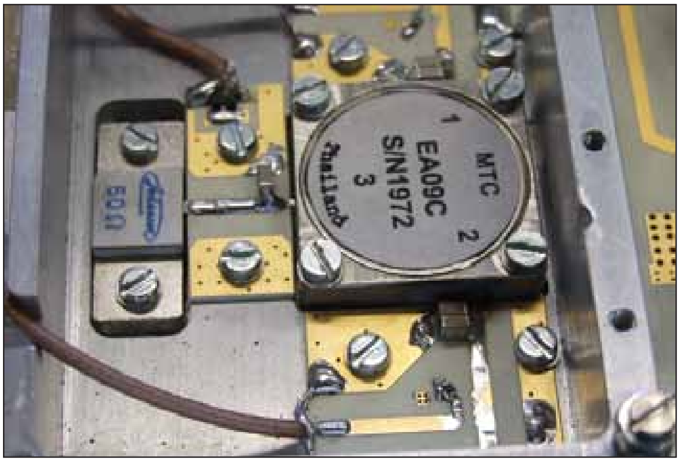

Figure 6 • Couplers and the isolator.

use of an NXP BLF25M612 LDMOS (Laterally Diffused Metal-Oxide-Silicon) power transistor, which offers an efficiency of greater than 50%. It is interesting to note that HHF's previous preamplifier design using a different power device occupied the exact same board area, while offering an efficiency of only 25%.

However, according to HHF, the most complex part of the design process was the power amplifier: HHF tested many different types of transistors and experienced considerable difficulty in finding a device that could offer appropriate stability and efficiency characteristics, before finally selecting NXP's BLF2425M7L250P LDMOS power transistor, which fulfilled all the necessary requirements. Electrical characteristics of the NXP LDMOS power transistor include: 28V operating voltage; quiescent current of only 200 mA; and based on typical continuous-wave performance at 2450 MHz, the transistor delivers an average output power of 250W with a typical power gain of 15 dB and an efficiency of greater than 50%, and typically up to 55%.

A power isolator is also implemented in the system, which allows the continuous-wave operation of completely mismatched loads. The power part of the SNA that includes the isolator—a circulator with a power resistor—is shown in Figure 6. The placement of the couplers—one before and one after the isolator—in addition to the isolation performance of the couplers are the determining factors in achieving good overall performance. The isolation of the couplers is greater than 25 dB and the flatness of the S11 measurement is less than ±0.5 dB.

Automotive and the 'Singing' Spark Plug

Overall, the SNA-based generator's output levels vary between 1 to 200W for continuous-wave applications at 2.45 GHz, with a peak power of up to 240W for pulsed applications and a transistor efficiency of approximately 51%.

A highly interesting application for the system is a spark plug for gasoline engines. The key advantage of this concept, when compared to a conventional ignition system, is the easy variability of the ignition time and duration, which enables the ignition to burn any residual gasoline in the chamber and results in significant exhaust reduction and fuel saving. Continuous electronic control enables the plasma to combust fuel with more efficiency, potentially up to 15% higher, which significantly reduces the carbon footprint of the next generation of automotive engines.

Operating at power levels varying between 10 and 200W, the three-stage transformer network generates a peak voltage of approximately 3.5 kV at the electrode to ignite the air/fuel mixture, enabling plasma ignition and sustained operation under atmospheric, low and even very high-pressure conditions (from 1mbar to approximately 220bar), with the case of the spark plug tied to ground.

To showcase the technology, NXP Semiconductors is currently using the system to demonstrate automotive spark plug applications, including a recent a demonstration at the 60th International Microwave Symposium in Montreal, Canada, June 2012. The demo uses the transistor device mentioned above—the BLF2425M7L250P—running at 2.45 GHz and delivering 250W with an efficiency of up to 52%. Running the spark plug in continuous-wave mode, rather than in the pulse mode as would be typically used in a car engine, meant that NXP engineers could modulate the 2.45 GHz RF continuous wave signal with the audio output from a typical consumer radio, essentially modulating the plasma at audible frequencies and making the demo spark plug "sing." Although in this particular case it could be described as a piece of fun engineering rather than an actual design goal, in other applications modulation can be very useful. For example, "acoustic plasma modes" are used to stabilize plasma arcs in RF lighting applications.

Enabling RF Energy

In essence, it is the increasing power efficiency and the decreasing "dollar per watt" metrics of the latest silicon LDMOS power transistors that are opening up new possibilities for RF energy. Over the past two years in particular, the product performance and cost structure of LDMOS has improved greatly. Key characteristics in this emergence are device power density, extreme ruggedness and outstanding efficiency. As an example, NXP's new range of 2.45 GHz ISM solid-state LDMOS power amplifiers, which all use thermally-enhanced packages, include: output power levels from 12W to 300W in continuous-wave operation; best-in-class efficiencies of greater than 52%; and field-proven ruggedness and long-term reliability, which enables these transistors to drive the typically mismatched loads of ISM applications. As a final note, NXP is also leading the way in this area with the development of Gallium-Nitride based RF power transistor devices that can handle even higher levels of power and deliver increasing levels of efficiency, further enabling new applications for RF energy.

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[1] Reference: Heuermann, H., Holtrup, St., Sadeghfam, A., Schmidt, M., Perkuhn, R., Finger, T., Various Applications and Background of 10-200W 2.45GHz Microplasmas, 60th International Microwave Symposium, Montreal, June 2012