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Plasma Power Supplies Inspired by Telecommunication Amplifiers

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ABSTRACT

Layers for solar cell manufacturing, display technology and semiconductor production require precise and efficient PVD and PECVD coatings as well as plasma etching processes. There is a trend to higher frequencies for plasma applications to increase the productivity or even allow new applications. Also, depending on the application a variety of different power levels are needed. These requirements had led us to develop and bring to market a new approach for the architecture of plasma generators designed in a platform approach. Inspired by telecommunications industry we adapted their technologies for the industrial plasma power supplies. The latest generation of LDMOS transistors, amplifier classes and envelope tracking as used in transmitter base station will also fulfill the stringent ruggedness requirements of plasma applications. The sophisticated planar PCB design from base station amplifiers is adjusted in terms of higher power level and frequency and brings the advantages and experience from high volume production to the industrial power supply. The new platform concept presented here can be adapted to different HF/VHF- frequencies and power levels of up to 40 kW. Together with the established TRUMPF Huettinger power combining topology which enables cable independence, as well as high plasma stability and a completely new metrology system this amplifier development impressively shows the change from piece manufacturing to a highly industrialized and reproducible production leading to rugged and repeatable high-end products.

INTRODUCTION

The frequency used for plasma excitation has an important influence on the process. As is widely known, the plasma density rises with frequency and faster deposition or etch rates could be achieved. The benefits of higher frequencies than the widely used 13.56 MHz, 40.68, 60 or even 81.36 MHz are discussed in [1]. With the increase in frequency, the designs for power amplifiers (PA) converge to those of telecommunication amplifier technology.

The amplifier design for plasma excitation is commonly based on classical power electronics topologies like class D or class E based on VMOS high voltage switching MOSFETs. These circuits consists of typical power electronics components like ferrites, wounded transformers and coaxial cable balanced to unbalanced transformers (balun). A “balun’ is a circuit used to balance an unbalanced system. Often these components are bulky and need air cooling. They do not allow automated assembly machines called “pick and place” and mostly require hand soldering. High tolerances lead to tuning steps during production. An example of this is the tuning of air coils by bending the windings or selection of matching values for capacitors. This makes the assembly fault- prone. Also the start-up of this power amplifier is time consuming. This leads to insufficient quality and bad reproducibility.

Development of amplifier technology was driven by the telecommunication market, which lead to new amplifier classes and designs. The requirements in terms of reproducibility and quality in this market, with the much higher piece numbers, prompted for optimized designs.

Inspired by the planar designs used in base station amplifiers, we adopted these technologies, to develop a platform for VHF plasma excitation. The PA PCB board is no longer used only for populating the components and connecting them. Components like balun, filters and even cooling functions are integrated into the PCB. A fully automated assembled PA on single PCB is the outcome of the process.

On the basis of the TRUMPF Huettinger TruPlasma VHF series 3010 (G1/40), a 10 kW 40.68 MHz generator, the new design of an RF plasma generator will be discussed in this paper. The advantages of this technologies and the impact on the application are presented.

DESIGN

Figure 1 shows the block diagram of the 10 kW RF stage. The input signal is sent from the control logic system to the driver. The driver preamplifies the input signal sufficiently enough for 8 PAs to generate the required power. A balanced amplifier configuration is used; in which 3-dB coupler produces quadrature phase shift between the outputs. Furthermore to create the input signal for 8 PAs in-phase splitters are used. Each of the PAs are provided with appropriate input matching networks (IMN) and output matching networks (balun) followed by a filter. The output signals are then combined again with 3-dB quadrature couplers followed by an in-phase combiner. The combining topology using 3-dB quadrature coupler makes the generator insensitive against cable length variations. The output power is measured with a directional coupler which is monitored by the control logic system.

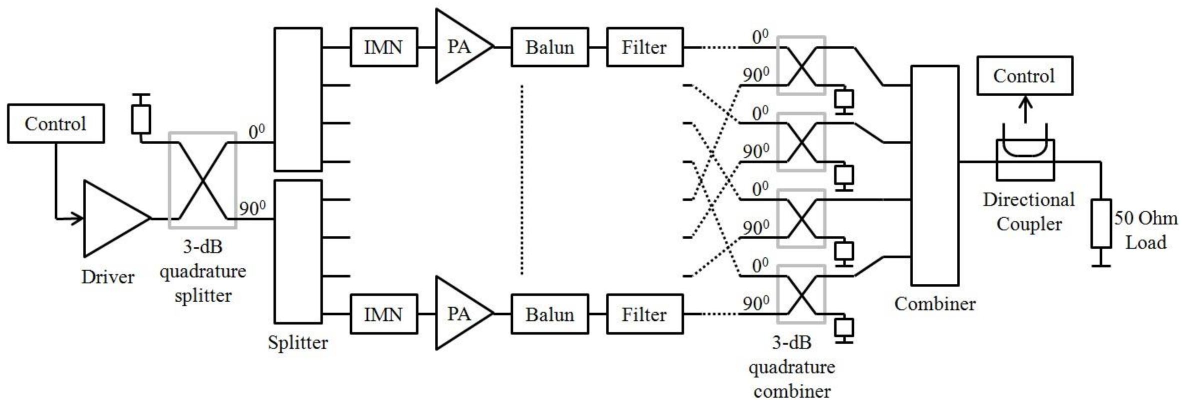

Figure 1. Block diagram of the RF stage topology

This paper is organized in the following sections based on key technologies:

- LDMOS
- Inverse class F amplifier
- Planar design
- Envelope Tracking
- Signal Generation
- Combining topology
- Metrology

LDMOS Transistor

As shown in [2], the Laterally Diffused MOS transistor (LDMOS) is the dominant device technology in broadcast and base station RF power amplifier (PA). In the 1990s, LDMOS gained wide acceptance for cellular infrastructure PA applications. A few years ago, the technology was evolved to a 50 V process for the applications outside of cellular infrastructure. These devices target the broadcast, commercial aerospace, industrial, scientific and medical (ISM) applications.

The high power, gain, efficiency, low cost and outstanding reliability makes this devices very interesting for such applications. Due to the ruggedness, the newer generation has demonstrated perfect use in more challenging applications like plasma excitation.

The 50 V LDMOS shows excellent thermal behavior for both pulse and CW applications. In [2] the very low thermal impedance is demonstrated, which leads to excellent mean time to failure (MTTF) numbers.

Inverse Class F Amplifier

The different amplifiers classes are defined by their bias point and output matching network technology. This means that each PA class has appropriate voltage and current waveform presented at the transistor output plane. The shape of the voltage and current waveforms define the overall performance such as output power, efficiency and gain.

The class F and inverse class F amplifiers classes provide high efficiency and output power due to their non-overlapping property of the voltage and current waveform at the transistor output (Figure 2).

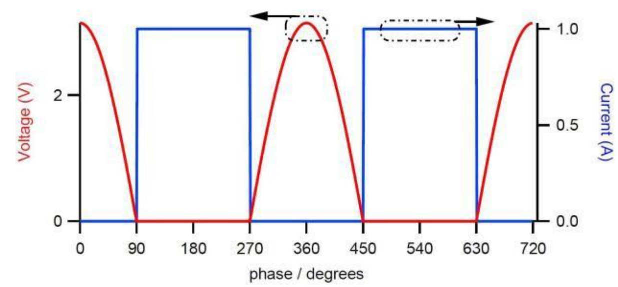

Figure 2. Idealized voltage and current waveform at the transistor for inverse class F power amplifier [3]

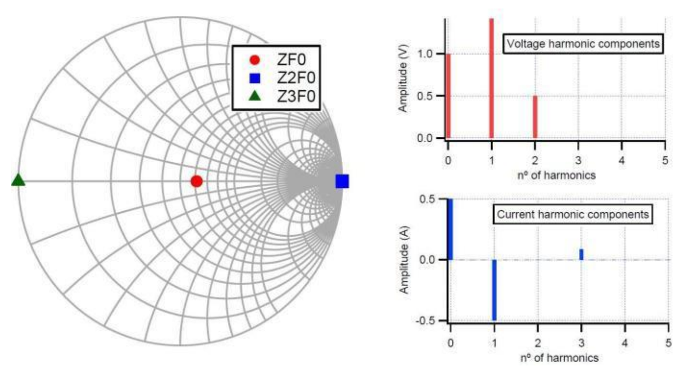

Figure 3. Idealized harmonic termination in the Smith chart (left) along with voltage and current spectral components (right) for inverse class F operation [3]

The inverse class F power amplifier can achieve high efficiency and high power by using appropriate harmonic terminators in the output matching network. These harmonic terminators shape the voltage and current waveforms of the active device so that high efficiency modes can be observed. Ideally for the inverse class F amplifier, the load must be short for all odd harmonics and open for all the even harmonics, as shown in Figure 3. In practical realization, only the first three harmonics

are considered, as all other higher harmonics are shorted by output drain capacitance. This results in the output current of the active device having square shape and while the voltage approximated to a half sine wave shape.
The inverse class F operation has higher efficiency due to the higher voltage peak at second harmonic when compared to class F operation which is contributed by the open load second harmonic termination.

Planar Design

The amplifier presented in this paper uses a planar balun (balanced to unbalanced) design approach, a type of transformer that converts the balanced output of the push-pull power amplifier to unbalanced output of the RF stage with respect to ground. There are different options for designing a balun like wire transformer style or a wound coaxial cable approach. We have chosen a planar stripline-type design integrated into the power amplifier PCB. Such a design is not as bulky as conventional baluns and has higher reproducibility and better thermal performance. The more complex realization of such an integrated design was solved by thorough and complex simulations. In [4] an approach for such simulations is described. The balun also acts as an impedance transformer that contributes to the matching circuits.

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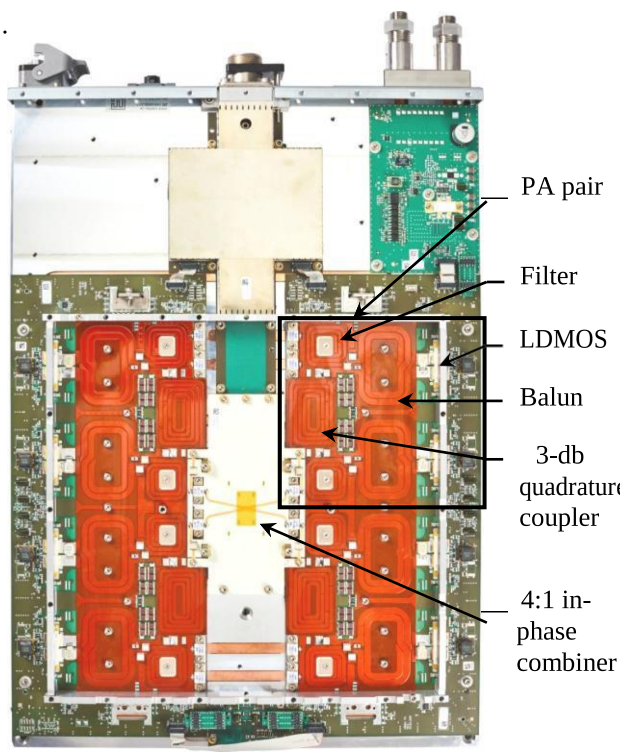

Figure 4. Picture of the 10 kW 40,68 MHz RF stage consisting of 8 LDMOS stages, four 3-dB couplers and one 4:1 in-phase combiner

Adding a filter to the output of each push-pull stage using printed stripline inductors improves spectrum of the generator over the whole frequency range. Following the filter a 3-dB coupler as a first stage combining element is realized on the same PCB. The 3-dB coupler is also designed based on the microstrip coupled transmission lines. With the planar design approach different structures like balun, filter and hybrid combiner can be integrated into a single PCB, thereby providing ease of manufacturing for mass production with less deviations and better performance.

Envelope Tracking

Conventional RF amplifiers with a fixed supply voltage have high efficiency and high output power when operating in compression mode. The specified efficiency of these amplifiers can only be achieved at maximum output power. As plasma generators are often operated below nominal output power the efficiency is typically far less then stated. In Figure 5 the power sweeps for fixed supply voltages are plotted and corresponding efficiency plots are shown in Figure 6.

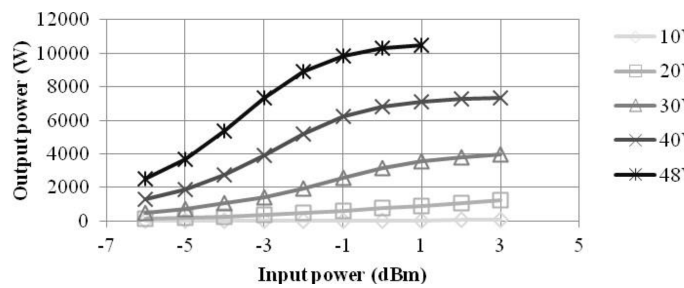

Figure 5. Measured output power versus input power of the PA for different supply voltages

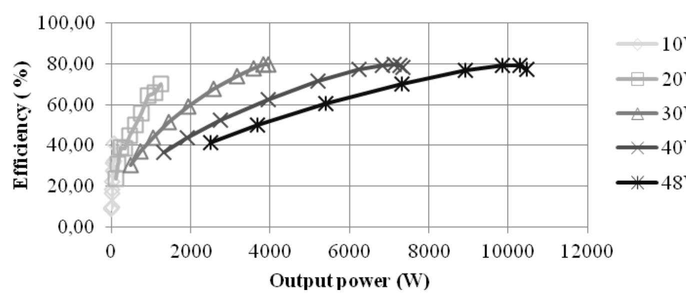

Figure 6. Measured efficiency versus output power of the PA for different supply voltages

To realize an amplifier with high efficiency over a broad power range the envelope tracking defines an approach to adjust the supply voltage of the amplifier. This means that the amplifier stays in compression over the whole output power range.

The fastest way to control the output power is through the variation of input power level. This control method allows set point changes in the µs-range. The disadvantage of this regulation method is reduced efficiency at lower input power levels. Another method is to control the DC supply voltage allowing higher efficiency over the whole output power range. This regulation method requires more time (typically ms) to adjust the supply voltage. Combining both regulation methods leads to high efficiency over a broad output power range along with faster regulation.

The supply voltage control is not required to have the same accuracy as the input signal due to the fact that the final amplitude regulation can be done with the input signal and thus lead to a correct output power level.

Signal Generation

Besides envelope tracking, as discussed in the chapter before, a very fast digital signal generation allows versatile options. In addition to fast rise/fall times, this digital signal creation allows various pulse pattern generation, e.g. multi-level pulsing, ramps or plateaus as shown in Figure 7. The generator's internal signal generation is based on an advanced digital modulation scheme.

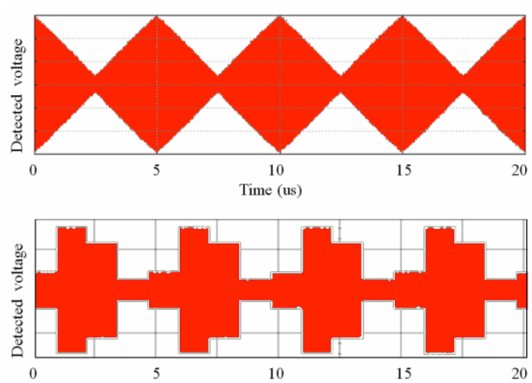

Figure 7. Advanced modulation schemes RF-signals [7]

This sophisticated pulse patterns could contribute to better process results or even make new processes possible.

Combining

RF Generators for plasma application require very high output power in the kW-Range and need to withstand full reflected power for short time. Typically single stages do not provide enough output power. For the 10 kW system in this paper, 8 PA stages were combined. The chosen topology of an RF-generator has a significant influence on the plasma operation. Widely used are in-phase combiner structures. A comparison of in-phase combining and balanced combining is explained in [5]. In-phase combining leads to unintended asymmetric output power characteristic into complex loads also known as'peaking'. The results are plasma instabilities and process yield impairment, resulting in a strong cable length sensitivity. During the ignition of the plasma this effect could clearly be observed. The comparison of the load characteristic between in phase combining (common generator) and balanced combining (TRUMPF CombineLine Technology) is shown in Figure 8. The TRUMF Huettinger patented balanced combining with 3-dB quadrature coupler also referred to as CombineLine reduces plasma instabilities. The topology chosen, involving 3-dB quadrature coupler combining in a first stage provides the advantages of balanced combining. The final combining stage is a 4:1 in-phase combiner.

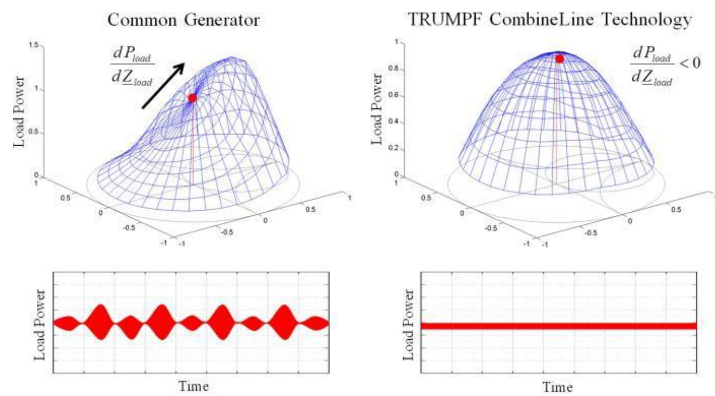

Figure 8. Load characteristic comparison (upper picture) of a common generator (left) using in-phase combining and the CombineLine Technology (right) and the effect on the time dependent behavior (lower pictures) [7]

Metrology and Control

Plasma processing tools require an extremely precise process control. The requirements according to accuracy in terms of output power and time resolution are getting more and more stringent. To cope with this trend a complete new control and metrology system was developed.

The modular and scalable control system bases on a Cortex A8 based processor with up to 1 GHz clock rate, which are also derived from mobile phone technology. The real-time operating system allows reaction times down to 1 µs while external signals attached to the internal programmable hardware (FPGA) like pulse input signal even allow response times well below 1 µs. The base board can be supplemented with various I/O-boards covering all common industrial interfaces (e.g. DeviceNet, EtherCAT, EtherNet/IP, Profinet). This architecture allows exact process timing.

The in-house designed directional coupler exhibits a directivity of >60 dB. A subsequent high resolution two-channel A/D-converter with an acquisition time of <10 ns feeds the digital demodulator with incident (forward) and reflected power signals. A multi-stage filtering allows both, an ultrafast response for best-in-class arc management (detection plus reaction <1.1 µs) as well as a smooth power and load phase determination. Special processing steps make the power measurement independent of frequency offsets or phase modulation

Various arc detection algorithms, including slopes and fixed thresholds, are selectable in the field. The units also have arc- sync inputs and outputs. Arc handling options include selectable power blanking times as well as burst pulses or self- prolonging handling with configurable retry limits.

Extra care is taken to calibrate the units with a floor standard traceable within ±0.65 % to the National Institute of Standards and Technology (NIST) standard. Thermally critically components of the generator such as the A/D-converter or the directional coupler are either in a thermostat-controlled environment or their temperature gradient is compensated in the digital domain. The resulting regulation precision is <1 % or <1 W over a wide dynamic power range of 1 W to 10,000 W.

The control allows continuous signal monitoring and acquisition of various parameters including power, temperatures, voltages, arcs etc. on the on-board or an external (USB) memory. User interaction is possible via the TRUMPF Huettinger PC-tool TruControl Power or a newly developed web graphical user interface (GUI) that can be presented with any common Internet browser.

CONCLUSION

The work in this paper demonstrated how technologies developed and proven in the telecommunication market can contribute to better RF plasma power supplies. Especially the development of the newest generation of LDMOS transistors brought the RF Amplifier design to a new level according to ruggedness. The planar design approach improves quality and reproducibility of the PA. Modern amplifier classes like inverse class F in combination with envelope tracking technique ensures high efficiency. Digital signal generation, fast sampling metrology and the CombineLine technology enable highly precise and stable plasma processes.

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