

A Computer-controlled System of High-power Microwave Sources

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Abstract—The paper presents the design and hardware implementation of a computer controlled system composed of up to four high-power microwave sources. Each source provides up to 200 W of continuous wave power. Frequency of each source is stabilized within ± 0.5 ppm of the nominal frequency adjustable within 2.35 - 2.6 GHz range. All four sources can be synchronized to the same frequency with computer-controlled phase shift between the signals generated by each of them. The paper concentrates on the choice of components for such a system and the properties of the realized hardware implementation.

Keywords—SiC, GaN, high power amplifier, PLL synthesizer, microwave sources.

I. INTRODUCTION

GENERATION of high power in microwave band was traditionally a domain of application of microwave tubes. Those tubes like klystrons or traveling wave tubes are quite expensive and inconvenient in application due to the necessity for high-voltage supply. Although the price issue has been solved in the case of magnetrons for domestic ovens, but such magnetrons have very poor spectrum and are difficult to control in amplitude, frequency and phase. The last decade brought a significant progress in availability and price of high-power transistors destined for microwave band. Transistor amplifiers are able to produce a pure signal obtained by amplification of a signal of a phase locked loop (PLL) oscillator. That signal can be computer-controlled in amplitude, frequency and phase. However typical range of application of such-constructed amplifiers is limited to tens of Watts of continuous wave power. Progress in microwave transistor technology opens a possibility of looking more bravely into the range of hundreds and in the future even thousand of Watts.

This paper presents a report on our effort to design and manufacture a system composed of up to four units, each of them generating up to 200 W of continuous power in the frequency band of 2.35 - 2.6 GHz. Output of each of the units is controlled in frequency and amplitude. Moreover the units can be driven from so called Master Unit producing signals of the same frequency and computer controlled phase shifts between them (adjustable in full 0-360 degree range). That way the obtained system is very flexible and can be used in many applications. Let us briefly mention two of them. One is high power testing of phased antenna arrays. Another one is generation of microwave plasma. The flexibility

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of the proposed system will give higher level of control of the process in terms of spacial distribution of the plasma inside the microwave plasma generator as well time-domain control of the process. However, applications of our system are not considered here in details and are planned to be subject of other papers. In this paper we report on our experience gained when designing the microwave power system using the best possible choice of components currently available on the world's market.

II. CONCEPT OF THE SYSTEM

To obtain sufficient flexibility of the designed system, it has been divided into three main parts: High Power Units (HPUs), one Master Unit and PC computer with dedicated software. An idea of connections between all of those devices is shown in Fig. 1.

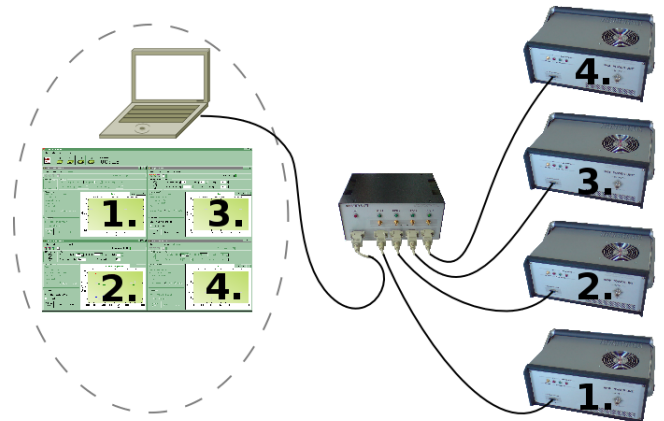


Fig. 1. The idea of the whole system.

Master Unit is a central device of the whole system. It connects together all High Power Units and PC computer into one system. It transmits the computer command to the HPUs. Furthermore, it is equipped with microwave PLL synthesizer and four digitally controlled phase shifters. Thus it can drive the HPUs with four microwave signals of same frequency but regulated relative phase shift between them in a full 360 degree range.

The main part of the whole system are four HPUs. Each of them can provide up to 200 Watts of output power in whole 2.35 - 2.6 GHz band. Power level can be changed in 1 dB steps. Each HPUs is equipped with detectors indicating the level of generated power as well as the level of power reflected from the load. The user can choose if the HPU is driven from its

TABLE I
HIGH POWER UNIT PARAMETERS

Output power	36 dBm ÷ 53dBm ± 1dB
Power change step	1 dB
Frequency coverage	2350 ÷ 2600 MHz
Frequency change step	1 MHz ± 0.1 MHz
Phase shift change range	0 ÷ 360°
Phase whift change step	5.625°
Output impedance	50 Ω
Output protection	Circulator with integrated dummy load
Power supply	230V AC 50 Hz

internal PLL or from an external source (that is the Master Unit). Parameters of the device are shown in Table I.

Dedicated software has been written for a PC computer to control described devices and to visualize measurements results.

III. HIGH POWER UNIT

Block diagram of the High Power Unit has been shown in Fig. 2. One housing comprises all modules necessary to provide 200 W of continuous microwave power that is: the control module, the power supply and the high power amplifier with a circulator protected output.

Control module consists of a local PLL synthesizer, an RF input selector, output power level regulators, 1 W power amplifier and power level detectors. All those peripherals are managed by a microcontroller.

A microwave signal source in the device is a PLL synthesizer built on an ADF4360-0 chip from Analog Devices [1]. The chip comprises a completely integrated PLL (synthesizer with VCO) controlled via SPI-similar interface. It has two differential outputs, but only one of them has been used. The oscillator covers full 2.35 - 2.6 GHz band with 1 MHz step even though it exceeds the lower limit of the frequency band guaranteed by manufacturer of the chip (2.4 GHz).

Selection of signal source (internal/external) is done by HMC545 chip from Hittite [2]. There was a problem with isolation between inputs. Value of -30 dB is given by the manufacturer in the datasheet, but it seemed to be not sufficient. In case of driving both inputs from two different PLLs, both set to the same frequency (but producing slightly different frequencies due the tolerance of the reference crystal oscillators), a nonlinear signal mixing was observed. Low frequency component of mixing was high enough to be detectable by the output power detectors as a variation in measurements results. The solution was to turn off the PLL which is currently not in use.

Just after the switch, the signal goes to the automatic level control circuit. Its role is to equalize the levels of signals from internal and external sources. The circuit has been built with AD8314 power level detector from Analog Devices and AT-108 analog attenuator from M/A-COM.

The module allows the user to change output power of the HPU. It has been based on HMC273 chip - digital 32 dB attenuator from Hittite. The chip is controlled by a 5-bit parallel bus directly from the microcontroller. It is possible to change the output power on low power level because all the

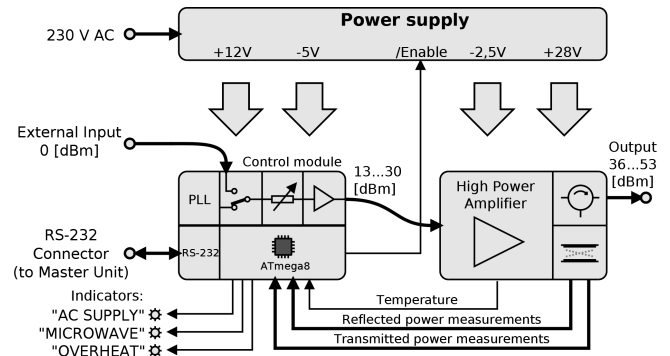


Fig. 2. Block diagram of High Power Unit.

following stages of amplification have been designed in A or AB class. Unfortunately, at the highest power levels slight non-linearity of the amplifier's transfer characteristic is noticeable.

At the end of the signal path of the pre-amplification there is an AB Class amplifier made with HJFET SHF289 from Sirenza. It provides 1 Watt of RF power for next block, 200 Watts high power amplifier.

Control module contains also carefully shielded AD8314 power level detectors from Analog Devices. They are used to measure output and reflected power of the HPU. Dynamic range of measurements is about 45 dB. Signals from the detectors are connected directly to A/D converter.

ATmega8 Atmel's 8-bit AVR microcontroller [3] has been chosen to be the heart of the module. It contains all necessary peripherals: hardware UART and SPI, 10-bit A/D converter and enough number of general purpose I/O pins. When new functions were being added it appeared that the microprocessor works at the limits of its memory. The problems have been solved by software optimization, but in the future designs we plan to use a processor with a bigger FLASH memory.

High Power Unit is powered by two modified typical PC computer power supplies connected in series. They give 28 [V] drain voltage for the 200 Watts amplifier. The amplifier is protected against damage in case of negative gate voltage failure - drain voltage is automatically disconnected when gate voltage is not sufficient to achieve the designed DC operating points of RF transistors.

IV. HIGH POWER AMPLIFIER

A. Choice of RF Transistors

There are many types of high power microwave transistors available on the market, but most of them are designed for pulsed operation (i.e. radar application). They are inadequate to build a continuous wave microwave high power source. One of the main problems which occurs, is a dissipation of the heat from active structure of the transistor. The wide energy band gap semiconductors, particularly Silicon Carbide (SiC) and Gallium Nitride (GaN) have become the new objects of interest due to their high breakdown voltage (both) and high thermal conductivity (SiC). Those properties make them the most suitable semiconductors to build high power high temperature microwave devices [4].

The SiC and GaN-based transistors can operate at very high temperatures without suffering from intrinsic conduction effects due to its wide energy band gap (n_i for SiC, GaN and GaAs is $5 \cdot 10^{-9}$, $1.9 \cdot 10^{-10}$, $2.1 \cdot 10^6$, respectively). They can also withstand an electric field E_B ten times bigger than Si or GaAs without a risk of the avalanche breakdown. This property enables fabrication of high-voltage and high power devices. Also it allows the active structures of transistors to be placed very close to each other, providing high device packing density for integrated circuits. In comparison to other semiconductors, SiC has an excellent thermal conductivity ($\kappa=4.9$). At the room temperature it is 10 times higher than GaAs. GaN has the thermal conductivity comparable to Si and almost three times higher than GaAs. This property enables SiC devices to provide extremely high power levels and still dissipate huge amounts of heat. Due to a high saturated electron drift velocity, which is two times higher than Silicon's and the same as Gallium Arsenide's, both SiC and GaN transistors can operate at microwave frequencies. The main disadvantage of these semiconductors is low electron mobility compared to GaAs. Although, in GaN HEMT structures, the electron mobility may achieve value of even 1600.

Therefore, SiC and GaN semiconductors seem to be most promising for application in high power continuous wave amplifiers. Unfortunately, transistors based on those materials are still poorly available on the market. Only three companies had such components in their offer - Cree (both), Eudyna (Fujitsu) and Toshiba (only GaN HEMTs). Furthermore, the fact of advertising of GaN and SiC products by manufacturers does not always mean that there are real possibilities to buy them. Sometimes the wishful thinking places the advertisement ahead of the real technological possibilities.

We have investigated the quality-to-cost ratios for both SiC and GaN transistors accessible on the market and decided that GaN-based HEMT transistors are currently the best choice for our HPAs.

B. Concept of the Amplifier

Despite a fast progress in semiconductor technology, it is still difficult to achieve 200 Watts of continuous power in the ISM 2.45 GHz band from a single transistor. Due to that fact, a structure of balanced amplifier has been chosen for our HPA - Fig 3. The whole amplifier consists of four 60 W amplifiers based on CGH27060 GaN HEMTs from Cree driven by two

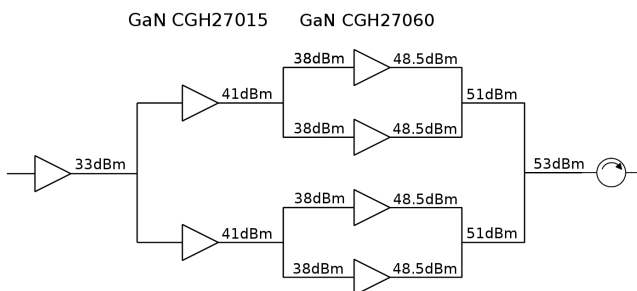


Fig. 3. The block diagram of the 200 Watts amplifier.

10 W amplifiers build with CGH40010 GaN HEMTs - both working in AB-class.

The input signal is divided between two stages by the power splitter designed with 3dB / 90° WIRELINE coupler from Sage Laboratories [5] . The same type of couplers have been used at the output for combiners, enabling summation of the power from the outputs of all amplifiers. To protect RF transistors against the consequences of a mismatched load, a 200 W circulator from Raditek [6] has been used together with an integrated dummy load.

The design process of the whole amplifier was aided with Agilent's ADS 2002 computer environment. It has been divided into four stages:

- 1) Build a 10 Watts driver amplifier
- 2) Build a single 60 Watts amplifier
- 3) Build a 100 Watts amplifier from two 60 Watts ones
- 4) Build a final 200 Watts HPA

C. 10 Watts Driver

The first task was to design a 10 Watts amplifier with gain of about 10÷12 dB destined for the first step of power amplification at the input of HPA. For that purpose we have chosen a GaN HEMT transistor - CGH27015 from Cree [7]. The datasheet states, that that device has a 14.5 dB small signal gain and is able to provide 15 W of the output power at 3 dB compression point.

The amplifier's design is based on the small signal approach and admittance condition for maximum output power. This condition is defined in a virtual reference plane of current source of the equivalent circuit [8]. That plane is placed inside the transistor and thus we need to design an input matching section transferring that condition to the physical input of the transistor. The input matching section was tuned to achieve maximum gain in the band of our interest (2.35 - 2.6 GHz in our project). Output matching section was tuned for optimal load impedance of the transistor to achieve maximum output power. At the same time the stability factor had to be controlled - it must be higher than 1 (minimum 1.1 - 1.2) for wide range of frequencies (usually 0.1 - 10 GHz).

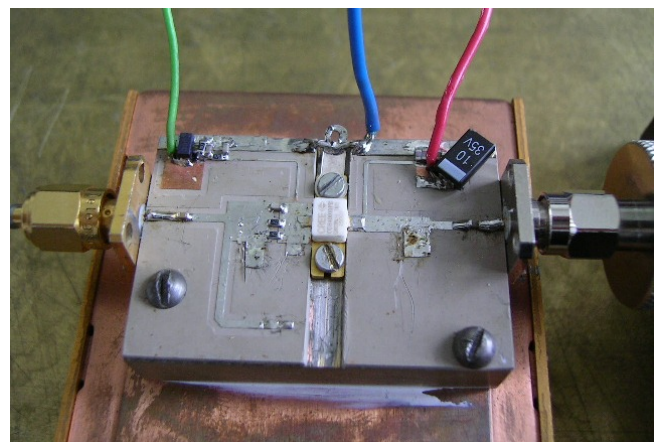


Fig. 4. The view of 10 Watts amplifier with CGH27015 GaN HEMT transistor.

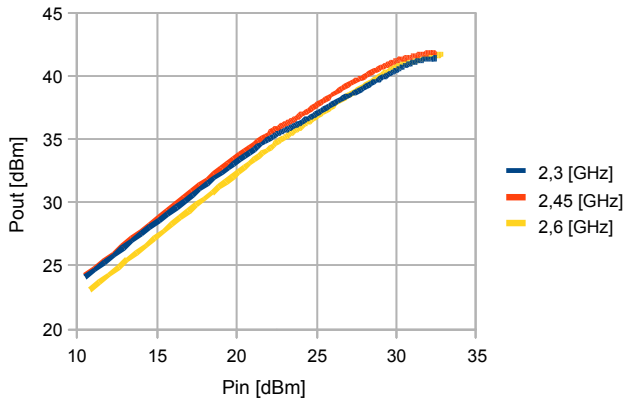


Fig. 5. Output power versus input power of the CGH27015 amplifier.

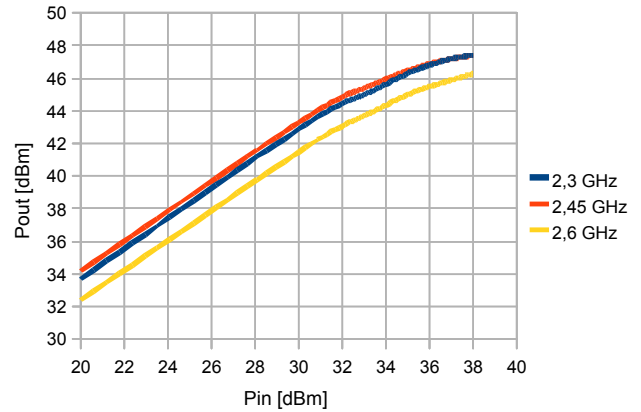


Fig. 8. Output power versus input power of the CGH27060 amplifier.

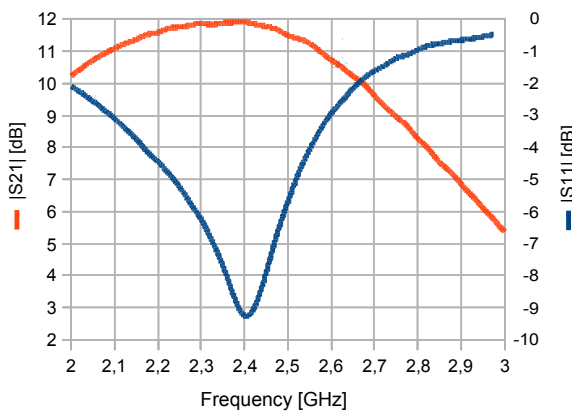


Fig. 6. Input reflection and small signal gain of the CGH27015 amplifier.

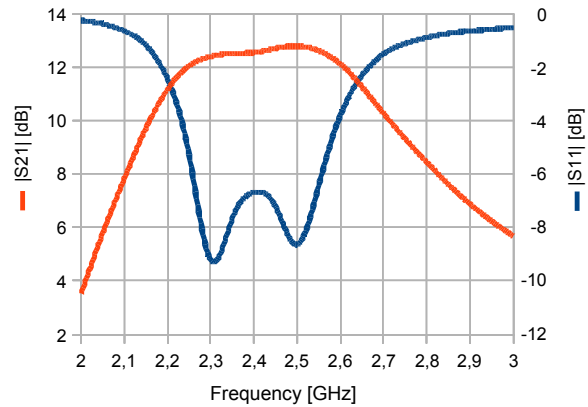


Fig. 9. Input reflection and small signal gain of the CGH27060 amplifier.

The view of the amplifier is presented in Fig. 4. It was possible to get 42 dBm of output power (Fig. 5) with 12 dB of small signal gain in the middle of the band (Fig. 6).

D. The 60 Watts Amplifier

The second part of the project was to design a single 60 Watts amplifier, which is presented in Fig. 7. As mentioned above, the CGH27060 GaN HEMTs were chosen for that stage. Those are high gain and high efficiency transistors supplied by Cree. They are described by the manufacturer

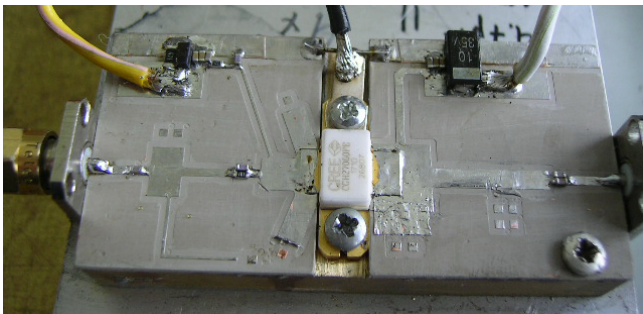


Fig. 7. The view of the 60 Watts amplifier with CGH27060 GaN HEMT.

as having more than 13 dB of small signal gain in 2.3 - 2.9 GHz band. The design procedure was the same as previously applied. After fabrication some final retuning had to be done. It was possible to get 47 dBm (Fig. 8) of saturated output power with a flat small signal gain characteristic at 12.5 dB in almost full 2.3 - 2.6 GHz band - Fig.9.

E. The 100 Watts Amplifier

Two 60 Watts amplifiers, based on CGH27060 transistors in the mirror image configuration were used to obtain a 100 W unit. The input power was divided between two HPAs by a splitter based on the WIRELINE type of coupler. Output power was combined by the adder of similar construction. As a four port coupler, WIRELINE introduces a 90° phase shift between its outputs, but by using a mirrored configuration at the output relative to the input, it was possible to eliminate that phase shift. The whole unit delivers about 12 dB of power gain and enables to achieve 100 W power level at the output. The view of the amplifier is presented in Fig. 10.

F. The 200 Watts Amplifier

To finalize the project, a 200 Watts amplifier had to be built. The idea was to connect two 100 W amplifiers described

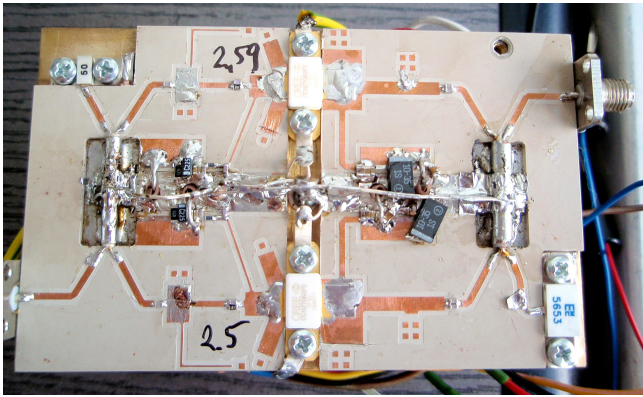


Fig. 10. The view of the 100 Watts amplifier with two CGH27060 transistors.

above in the same manner as it was done with 60 Watts HPAs. Four 60 W transistors should give desired power with some redundancy for losses and not ideal impedance matching. The theory was quite simple, but the real world was not. Several problems were encountered before finalizing the project.

High level of the output power caused problems with electrical breakdown of the PCB's dielectric or the circulator. As the amplifier's base, 1.6 millimetres thick Taconic CR10 laminate was used [9]. The component connections must be smooth and clean to avoid local irregularities of the electric field which may lead to arcing causing the circuit breakdown.

In order to minimize mutual influences of individual amplifiers, the whole amplifier module as well as all elementary sections had to be carefully shielded. The dimensions of the shield cells are comparable to the wavelength which increases the danger of uncontrolled field resonances inside the metal boxes. We found that the shield should be made rigid to avoid uncontrolled change of the shape of shield cells.

The amplifier module was protected against mismatched load by a miniature circulator and dummy load installed at the output. It was equipped also with output and reflected power level detectors. We have measured that the circulator provided about 25 dB isolation between its arms in the middle of the band.

The efficiency of the amplifier is about 60%. This means that it is necessary to dissipate in it an amount of power almost equal to the output power. Huge heatsink with two efficient fans have been used. The temperature of the the device working at the full power level stabilizes at 55°. The output power level decreases by about 1 dBm during heating process.

The whole 200 Watts amplifier is shown in Fig.11 with top shielding dismantled.

V. MASTER UNIT

Master Unit has two main roles in the described system. It acts as a message delivery hub between PC computer and High Power Units and also it is a source of four low power one-frequency microwave signals with a possibility to change the phase shift between them. The block diagram has been shown in Fig.12.

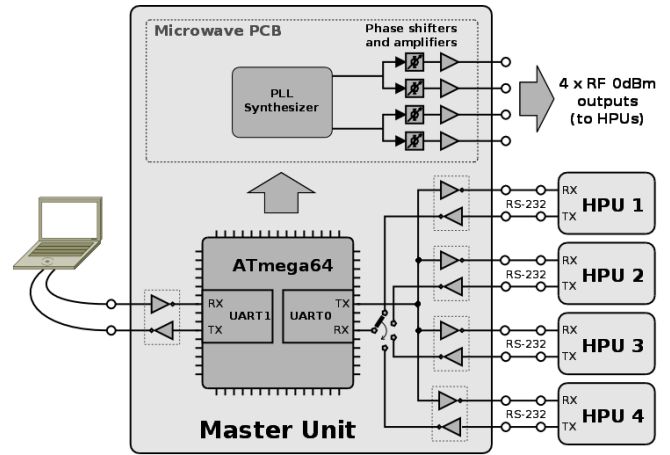


Fig. 12. Block diagram of Master Unit and its interface system.

The PLL synthesizer is realized with ADF4360 chip from Analog Devices. It is very similar to generators used in High Power Units, but both outputs of the chip have been used here.

Phase shifters block consists of four HMC647 chips by Hittite. Thanks to them, the system user may change the relative phase shift between any of the four output signals in full 360 degrees range with a step of 5.625°. They are controlled by 6-bit parallel buses, which are connected directly to the ports of the microcontroller. Power level on each output of the Master Unit is about 0 dBm.

All features of the Master Unit are controlled by a ATmega64 - fast 8-bit AVR microcontroller from Atmel. It provides sufficient number of I/O pins and two integrated UARTs. Both UARTs are hardware implementations of multi-mode serial transmissions. In this design asynchronous mode compatible with RS-232 standard has been chosen.

VI. SOFTWARE

A. Windows Application

Special application (*SSMG Controller*) has been developed to make use of the described system more comfortable. It provides good "look and feel" as well as easy access to many modes of the system operation. User is allowed to choose between single frequency excitation, scanning in a defined band or auto-finding of a lowest reflection frequency.

Each HPU has its own window, where parameters setup can be done. Measurements results are displayed on resizable graphs. User can save acquired data to a file or print them. HPUs may work together at the same time (i.e. with common excitation signal source) or they might be used independently (*Single HPU Mode*).

The software has been written in C# language in Microsoft Visual Studio 2005. It can be executed on computers with Windows-family operating systems. LGPL licensed *ZedGraph* component [10] has been used to display measured data.

B. Firmware

Software for microcontrollers has been written in C language using avr-gcc compiler. The GNU GPL *Procyon*

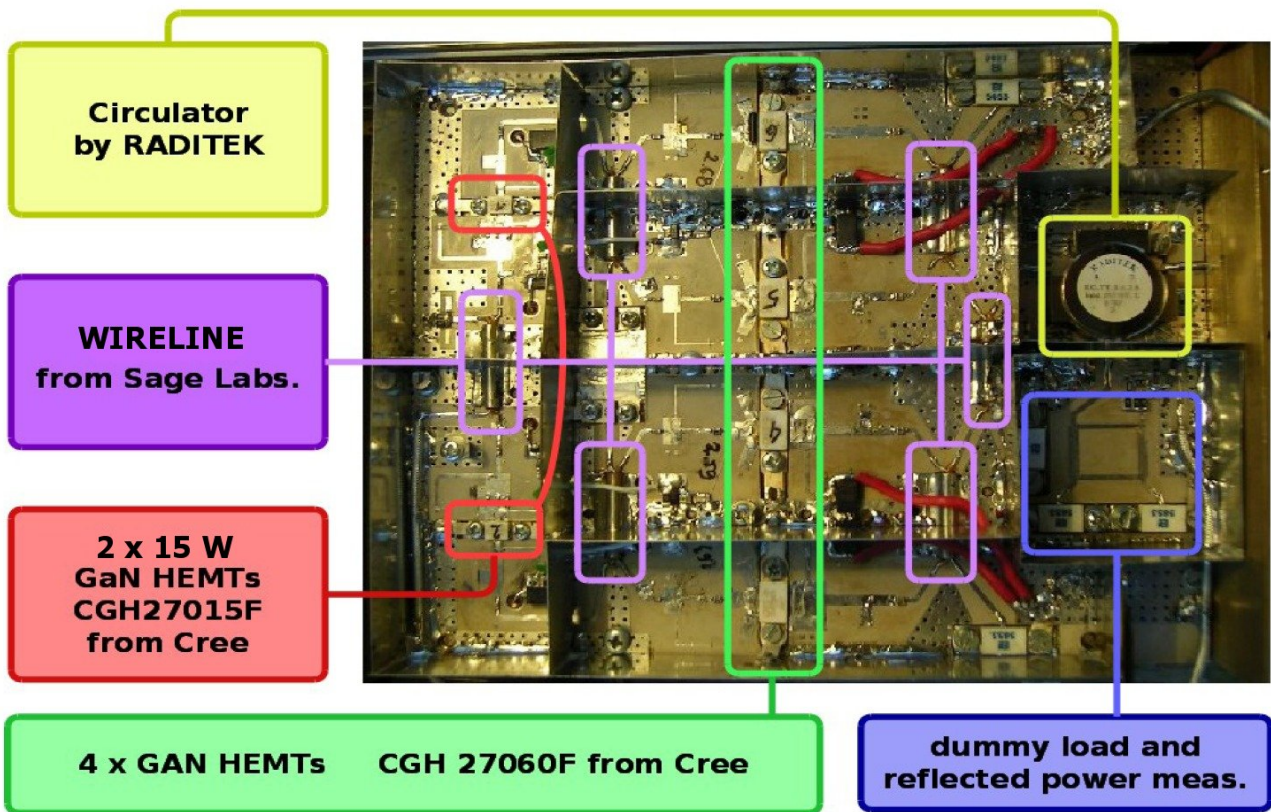


Fig. 11. The view of the final 200 Watts amplifier with four CGH27060 transistors. Main components have been pointed.

avr-lib library [11] has been used to speed up development of the software. Firmware can be upgraded via ISP port included in each device.

Communication via RS-232 is done with messages transmitted in plain ASCII text to make it readable for a human. It is possible to control the system via RS-232 terminal application, i.e. *Putty* or *minicom*. Special set of commands has been proposed to set up all parameters of High Power Units and Master Unit. The firmware allows also reprogramming of the microcontroller's EEPROM memory, where calibration parameters are saved.

VII. CONCLUSION

The design and manufacturing of a system composed of four 200 W 2.45 GHz-band solid-state microwave sources has been presented. Frequency of each source is stabilized within ± 0.5 ppm of the nominal frequency adjustable within 2.35-2.6 GHz range. All four sources can be synchronized to the same frequency with computer-controlled phase shift between the signals ranging from 0 to 360° with 5.625° step. The system has been designed in a flexible way so that many possible areas of its application can be envisaged.

Currently the technology based on GaN HEMT transistors seems to be the best choice for realization of such systems. The cost of GaN transistors is still relatively high but the authors hope that a fast progress in semiconductor technology will shortly bring the prices down making the described technology affordable in various areas of science and technology.

REFERENCES

- [1] Analog Devices Data.
- [2] Hittite Data.
- [3] Atmel Data.
- [4] R. J. Trew, "SiC and GaN Transistors – is there a Winner for Microwave Power Applications?" *Proceedings of the IEEE*, vol. 90, pp. 1032–1047, June 2002.
- [5] Sage Laboratories Inc.
- [6] Raditek: Wireless, RF and Microwave Telecommunication Solutions.
- [7] Cree.
- [8] W. Wojtasiak and D. Gryglewski, "A 100 W SiC Mesfet Amplifier for L-Band T/R Module of APAR," in *18th International Conference on Microwave Radar and Wireless Communications (MIKON)*. Warsaw University of Technology, MIKON, 2010.
- [9] Taconic RF & Microwave Laminates.
- [10] ZedGraph - C# 2D charts plotting component.
- [11] Procyon avr-lib.