Strong microwave electric field reached by a high power wideband amplifier for automotive application

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***Abstract*— Many automotive standards impose to generate high electric fields in microwave frequency bands. In this paper we present a microwave application developed for an automotive laboratory. The focus on the microwave amplifiers gives some specific solutions to reach the Ford and the requirements according to the Standard Specifications. The frequency range addressed is from 0.8 GHz to 4 GHz with an average output power up to 800 Watts for linear operation and up to 1000 Watts in saturation.**

***Keywords*— power amplifier, wideband, microwave, high field, EMC, immunity, radiation**

I. Introduction

The automotive standards require high electric field strengths [1] in different frequency bands. In low frequency, some applications have been presented in the past; in particular, a paper regarding a 12 kW power amplifier [2]. In this paper, a new technology has been developed [3] especially for microwave specifications.

For Ford or General Motors standard applications, this paper presents a specific test set-up using a microwave amplifier with 800 Watts typical output power. We focus on the strong electric field achieved.

This amplifier is a Gallium Nitride (GaN) solid state amplifier delivering a 800 W typical output power in the frequency range 800 MHz to 4000 MHz. Thanks to its class A operation, the amplifier provides a good linearity, -20 dBc max. is maintained in the entire frequency range.

Integrated in an automotive test-setup, a CW electric field is maintained up to 600 V/m in specific sub-ranges (1.2 GHz to 1.4 GHz & 2.7 GHz to 3.1 GHz).

In this paper, first, we have presented the different advantages of the GaN technology in high frequency and wideband amplification. On the other hand, we have been detailed the main characteristics of EMC high power amplifiers. Last but not least we give a description of the high power and wideband amplifier by presenting the key results. Finally, experimental data is presented for a typical automotive application.

II. High frequency band technology

This large gap technology appears as a strong technological breakthrough in the field of RF power transistors. This technology developed is a combination of two fundamental elements: Nitride and Gallium. The component power density is very high, more than 30 W / mm for some grid development. The width of the band gap of GaN (Gallium Nitride) is 3.39 eV. This quantity represents the amount of energy required to move an electron from the valence band (idle status) to its conduction band (excitement). It demonstrates the robustness of the material at elevated temperatures. As to silicon carbide, gallium nitride resists an electrical field greater than 3.106 V / cm. The breakdown field is the value of the electric field, which is supported by the component. More this characteristic, the greater the component will be able to withstand high bias voltages. For these materials, avalanche tensions are high in the order of hundreds of volts. The use of high bias voltages (≥ 50 V) is therefore possible with this type of semiconductor. For heat dissipation, the wide band gap materials including silicon carbide have excellent potential in this field.

First it was only used in some specific and discrete university projects. Ten years ago, only few manufacturers sold it. Gradually, different foundries developed their own spinneret.

This technology allows designing wideband microwave amplifier cells with a good linearity. The graph in figure 1 presents the main advantages of this technology compared to Si.

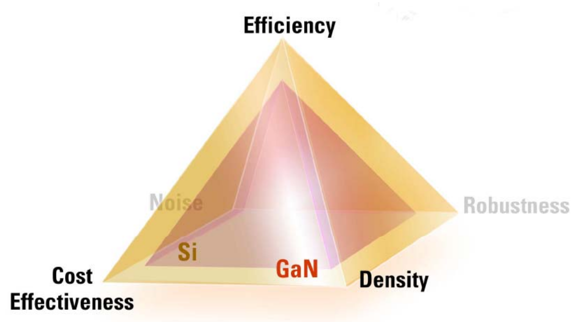

Fig. 1. *GaN technology benefit.*

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III. CLASS A OPERATION: PRESENTATION AND CHARACTERISTICS

In the literature, many articles [4] exist presenting the different class of amplification. In this section, class A is presented highlighting the main electrical characteristics.

First, power amplifiers are characterized by the output power, the input power and the DC power (see figure 2). Thanks to these three characteristics, we define the power gain (1) and the efficiency (2):

$$G_P = \frac{P_{OUT}}{P_{IN}} \quad (1)$$

$$\eta_P = \frac{P_{OUT} - P_{IN}}{P_{DC}} \quad (2)$$

These amplifier performances are often represented on a same graph (see figure 3).

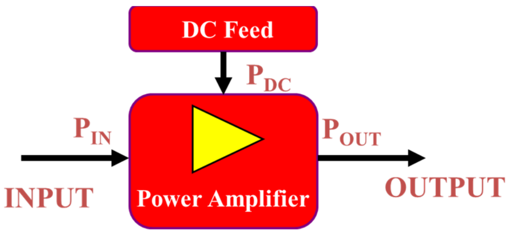


Fig. 2. *Power amplifier schema.*

In figure 3, the 1dB output power is defined as the boundary between the linear area and saturation. It is measured when the power gain decreases by 1 dB compared to its small signal value. The 3 dB output power is obtained with similar measurements. In function of the technology, the maximum of efficiency is located in the area between the 1 dB and the 3 dB compression power.

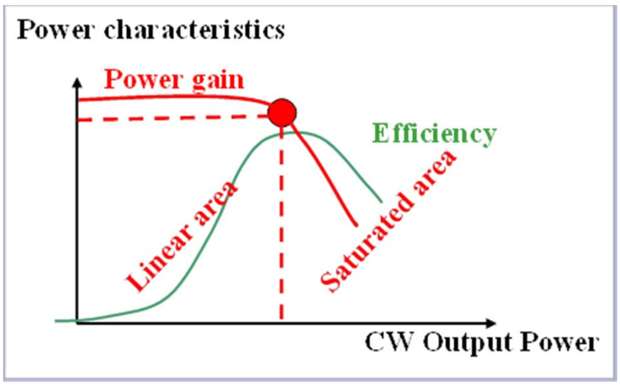


Fig. 3. *Amplifier typical characteristics.*

Another parameter is used for EMC system qualification: the linearity. In the literature, different techniques and parameters (Error Vector Measurements, Adjacent Channel Power Ratio, CW Harmonics) are described for characterizing the linearity. For EMC applications, CW harmonics are often used for calibration purpose. The harmonic ratio (3) or Harmonic rejection (H2 and H3) is presented in figure 4.

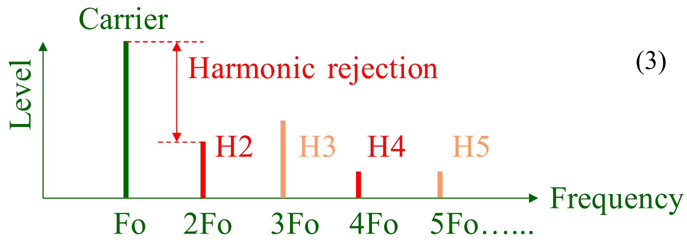
A minimum of 13 dBc terminated into a 50 Ω load is required for the EMC standard.

$$H_2(dBc) = Level@2F_0(dB) - Level@F_0(dB) \quad (3)$$

$$H_3(dBc) = Level@3F_0(dB) - Level@F_0(dB) \quad (4)$$

Where H: harmonics level,

F: Frequency,



(3)

Fig. 4. *Harmonic ratio measurements.*

IV. WIDE BAND AMPLIFIER DESIGN

We developed, designed and integrated a special 19-inch rack with 32 U cabinet using the GaN technology presented in section II.

This amplifier covers the frequency range from 0.8 GHz to 4 GHz. It is able to deliver a typical output power up to 800 Watts with a 50 Ω load (curves presented in section V).

Its modular and modern design is composed by four final identical power racks, only one final combiner is used to combine an important output power up to 4 GHz (see figure 5). A dual directional coupler is part of the output to indicate the incident and the reflected output power levels.

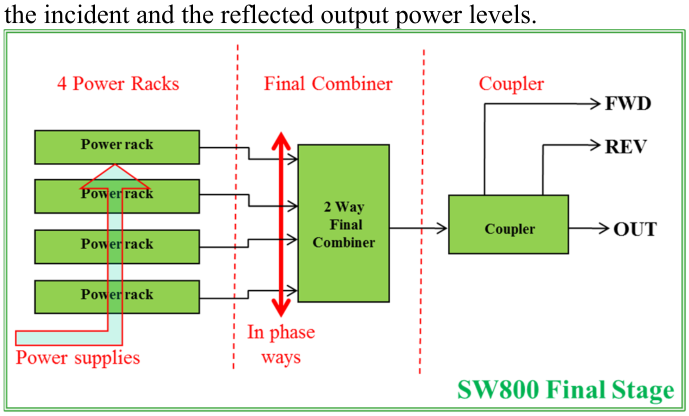


Fig. 5. *Final stage description.*

This modular concept requires to design the power racks with the same power characteristics: power gain and phase. The four-phase output signals are essential to achieve the best combination.

Each power rack uses the same amplifier modularity described above. In fact, it integrates eight final power modules. The same constraints of phase and power gain are necessary.

Out target during the design phase was minimum of maintenance effort: easy accessibility of all sub systems and all the modules is an advantage for an easy exchange or replacement and upgradable solutions. This design allows a fast and efficient after sales service across the globe.

V. MICROWAVE AMPLIFIER POWER MEASUREMENTS

The amplifier was tested in a typical power test set-up (see figure 6). It is composed by a state-of-the-art network and spectrum analysers. Due to the high level of power, special attenuators and connectors have been developed and manufactured up to 4 GHz. The complete measurement chain is automated and calibrated to harmonize the results.

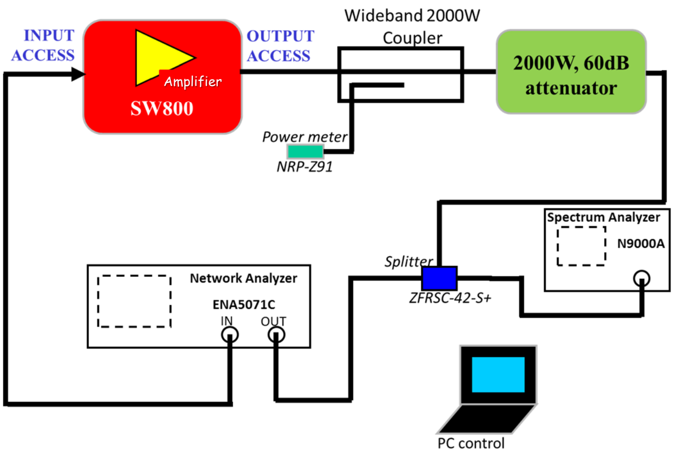


Fig. 6. *High Frequency Power Test Setup.*

With this test bench, we are able to measure the main amplifier specifications:

- The small signal gain
- The output power at 1 dB and 3 dB of compression
- The harmonic ratio

A. Output power

All the measurements presented in this sub-section has been performed according to the theoretical techniques detailed in section III.

In figure 7, we have shown the output power curve at 1 dB compression point (see green line) and at 3 dB (see red line) respectively. This amplifier delivers a minimum linear output power up to 600 W in the frequency range from 0.8 GHz to 3.6 GHz. A derating of only 50 W was measured up to 4GHz. At a maximum, the amplifier is able to deliver a saturated output power up to 1700 W.

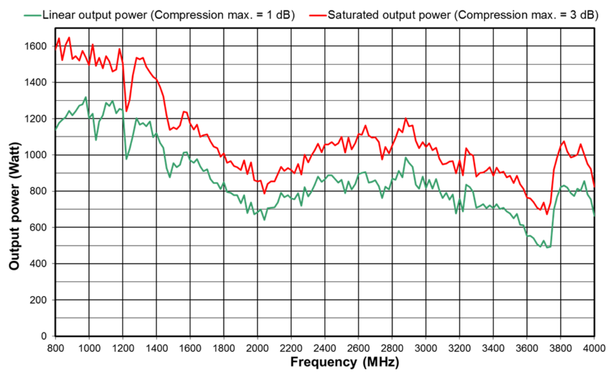


Fig. 7. *Measured output power (frequency step = 20 MHz).*

The maximum output power is provided at the beginning of the frequency band in order to compensate the lower gain of most wideband antennas.

B. Harmonic measurements

Each of wideband amplifier are considered as linear if their harmonic rejection is down to -20 dBc. The class A operation chosen for this design permit to have a good linearity (< -20 dBc) across the entire bandwidth (see figure 8). The green curve represent the 2nd harmonic ratio and the black one the 3rd harmonic rejection.

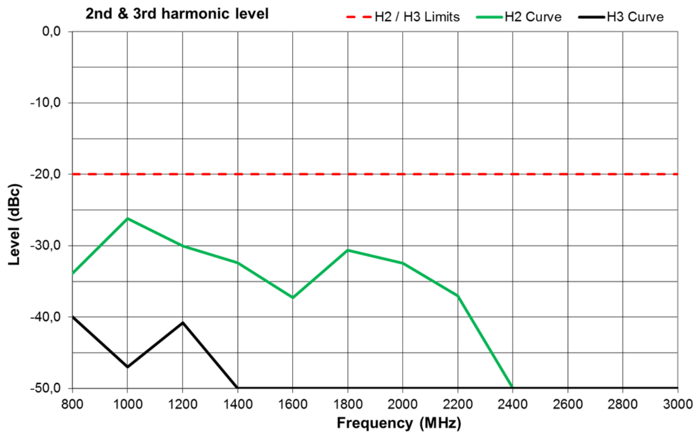


Fig. 8. *SW800 harmonics.*

The end of this paper is dedicated to a typical automotive application.

VI. AUTOMOTIVE APPLICATIONS

Throughout the development and the design phases, we took into account the specific automotive application related to Ford [5] and General Motors standards [6]. In these two standards all the procedures for technical testing are presented. For example, the main requested characteristics [7] of testing chambers are available.

Our specific paper is based on the standard recommendation, from page 36 to page 39 for FORD Standard (table I) and the two pages 11, 12 for the GM Standard (table II).

TABLE I. ELECTRIC FIELD LEVEL EXTRACTED FROM FORD STANDARD

Band	Frequency range (MHz)	Level 1 (V/m)	Level 2 (V/m)	Modulation
4	400 - 800	50	100	CW, AM 80% Pulsed PRR = 18 Hz, PD = 28 msec
5	800 - 2000	50	70	CW, Pulsed PRR = 217 Hz, PD = 0.57 msec
6	1200 - 1400	n/a	300 600	Pulsed PRR = 300 Hz, PD = 3 msec, with only 50 pulses output every 1sec.
7	2700 - 3100	n/a	300 600	

In table I and table II, the different level requirements have been summarized. The specifications of each standard are quite similar.

TABLE II. ELECTRIC FIELD LEVEL EXTRACTED FROM GM STANDARD

Frequency range (MHz)	Level 1 (V/m)	Level 2 (V/m)	Modulation
400 - 800	50	100	CW, AM 80%
800 - 1000	50	100	CW, AM 80%
800 - 1000	50	70	PM PRR = 217 Hz, PD = 0.57 msec
1000 - 2000	50	70	CW, PM PRR = 217 Hz, PD = 0.57 msec
1200 - 1400	n/a	300 600	Radar pulse packets PPR = 300 Hz, PD = 3 µsec (+3/-0 µs) with only 50 pulses output every 1 s

Taking into account the formula for the generated electric field (4), only two parameters can be adjusted to reach the 600 V/m: the antenna gain and/or the output power of the amplifier. For wide-band applications, the antenna gain cannot improve indefinitely. As a consequence, the output power of the amplifier is the solution to reach the desired electric field.

$$E(V/m) = \frac{\sqrt{\frac{ZxGxPe}{4.\pi}}}{r} \quad (5)$$

The German test setup developed for this demonstration resume all the requirements required by the FORD and GM standards (see figure 12). The amplifier is associated with a SUCCOFED cable length 2.8 m to reach the chamber wall (n°10 in figure 9). A 7/16 feed-through allows passing through the wall (n°9 in figure 12). Another cable length 4.8 m (n°8 on figure 9) and 7/16 adapters are connected to a high gain horn antenna model AT4510 (n°6 on figure 9).

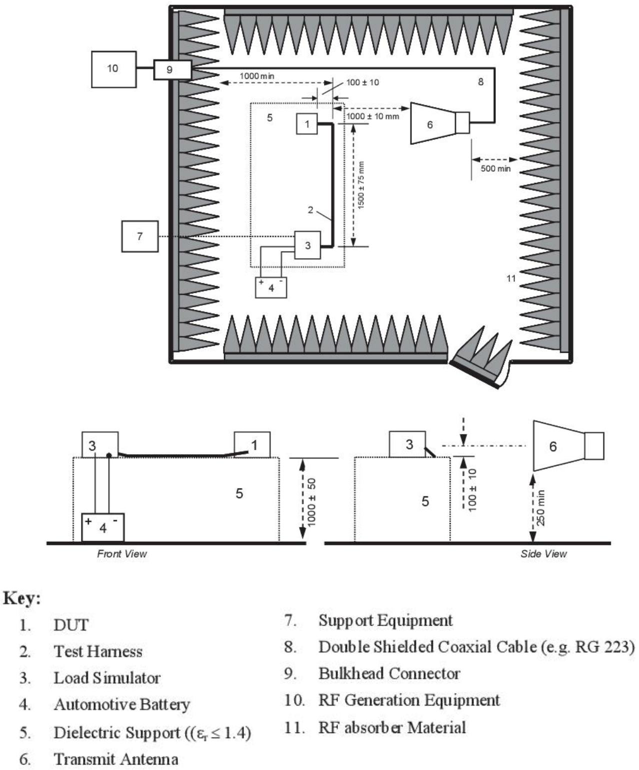


Fig. 9. *FORD Standard Test setup for band 6 and 7 (extracted from [5]).*

The obtained measurements in horizontal and vertical polarization are presented in figure 10 and 11. In all configurations, the electric field strength levels are conform with the specification; only at 1220 MHz, the electric field is close to the limit.

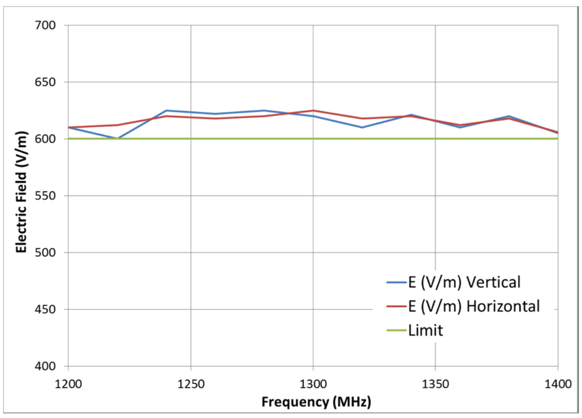


Fig. 10. Electric Field measured in the 1.2 GHz to 1.4 GHz frequency range.

In the frequency range from 2.7 GHz to 3.1 GHz, some measurement points are near to 650 V/m. The amplifier is running in linear area, so the harmonics are under the -13 dBc as requested by the standard.

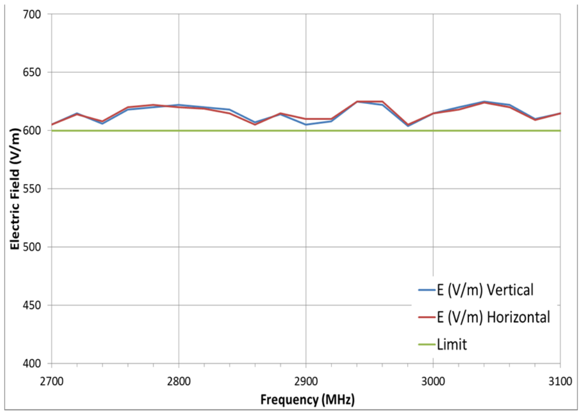


Fig. 11. *Electric Field measured in the 2.7 GHz to 3.1 GHz frequency range.*

VII. Conclusions

Different demonstrations have been presented in this paper focusing on a specific microwave amplifier. Typical FORD and GM applications are presented in this paper. All these measurements validate the combination of two main microwave frequency devices (antenna + amplifier) to generate high CW field levels (> 600-V/m) in the microwave frequency range. The GaN technology appears also to be the solution to generate strong electric field for microwave frequency.

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