Solid-state microwave power amplifiers of a super-octave band

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Abstract: *The paper includes the analysis of technical and technological solutions used in the design of ultra-wideband transistor microwave power amplifiers, as well as modern technologies and schemes for constructing monolithic integrated power amplifiers. The matters of design of high-power amplifiers and parameters achieved during development and production of amplifiers are reviewed in the publication.*

Keywords: *power amplifier, gallium nitride, monolithic integral circuit, ultra-wideband.*

1. Introduction

The use of power amplifiers with a frequency band of more than an octave (for discretion referred to as the ultra-broad frequency band) is always under the spotlight. Such attention is due to active development of the technology of active phased antenna arrays), both radar and anti-radar, the use of short pulse and noise-shaped signals requiring large instantaneous band of transmitting path, and transition to multifunctional and multi-band radio systems.

The combination of optimal circuitry implementation, rational design and advanced active devices technology ensures the successful development of high-performance ultra-broadband power amplifiers. Technical solutions and instrument parameters in this paper are considered in relation to the frequency range of 2 - 18 GHz, covering all the main radar (S-, C-, X-, Ku-) ranges and the most sought after (2 - 6 GHz, 6 - 18 GHz, 4 - 18 GHz) anti-radar frequency ranges.

2. Basic definitions

Let us compare the qualitative parameters of a transistor microwave power amplifier having various operating frequency bands. We consider a working frequency band to be such a section of the frequency range which matches all the given technical characteristics of the amplifier. Consider table 1 in relation to an elementary transistor amplifier stage.

Table 1

Parameters and characteristics	Narrowband amplifier	Broadband amplifier	Ultra-broadband
Frequency coverage	Less than 1.2: 1	From 1.2: 1 to 2: 1	Greater than 2: 1
Complexity of matching circuits	Simple, 2-3 elements	Medium difficulty, 3-5 elements	Complex, 5-11 elements
Implemented input voltage standing-wave ratio	Less than 2.0	High	High
Practical harmonic load control option	Extended	Limited	Next to none
Achievable electronic efficiency,%	Up to 80%	Up to 45-50%	20-30%
Frequency response unevenness	Next to none	Average	High
Hardware Efficiency	Close to electronic	Less than electronic	Significantly less than electronic

In this case, “hardware efficiency” [1] is defined as

$$\eta a = Pout.min / Pcons.max, \quad (1)$$

Where:

Pout.min - minimum output power in the working frequency band of an amplifier;

Pcons.max - maximum power consumption of the amplifier from the power source.in the operational frequency band.

The ηa parameter is important for system design and evaluation of energy consumption of a system during operation, and maximum output of a power source.

With high unevenness of output power and uniform electronic efficiency, the hardware efficiency of the ultra-broadband amplifier may be several times less than electronic, whereas the mastery of ultra-broadband amplifiers design is nowadays estimated by the results of increase of both the first and second parameters.

The improvement of ultra-broadband amplifier parameters is mostly connected with the improvement of parameters of microwave transistors and their production technologies, and those in turn are associated with development of microwave integrated circuit technologies and discrete gallium nitride (GaN) transistors. The goals of the projects reached during the last five-year period are laid out below.

3. Ultra-broadband amplifier component base

The discrete crystal-form transistors and monolithic integrated circuits (MMIC) based on GaN technologies remain the basis of the centimeter-wave ultra-broadband amplifier design. Let us consider the modern market of discrete crystal-form GaN transistors; the series available on the market and devices' parameters are provided in Table 2.

The nomenclature and variety of discrete GaN transistors introduced to the market had extended significantly during recent years. The traditional crystals manufacturers - Qorvo (TriQuint) and Wolfspeed (Cree) were joined by the French UMS and South Korean WavePia. Transistors produced by AMCOM Communications (USA) and Resonance LLC (Russia) utilizing NP25-00 foundry technology are also on the market. Svetlana-Rost JSC and Svetlana-Electronpribor are in the process of testing of crystals of in-house production. A number of Russian companies are developing microwave devices technologies based on gallium nitride, however no crystals are available on the domestic market yet.

The relatively low-voltage technologies with a gate length of 0.15 - 0.25 μm and operating voltage of 20 - 28 V are of the greatest interest for designing of ultra-broadband amplifier of the centimeter range. This is due to the fact that with increase of operating voltage the active part of the optimal load impedance, required for ensuring of maximum output power or efficiency, increases proportionally. Whereas it's reactive part, determined by the drain-source and drain-gate stray capacitances of the transistor, hardly changes. As a result, the intrinsic equivalent Q factor of the virtual output circuit also grows, which increases the complexity of ultra-broadband amplifier output matching circuit realization.

Table 2

Transistor type	Manufacturer	F, GHz	Pout, W	Efficiency, %	Gate length, micron	Ud, V
Transistors in production up to 2012						
TGF2023-2-xx	Qorvo	18	6 - 50	60	0,25	28
CGH600xxD	Wolfspeed	6	8 - 120	65	0,5	28
CGHV1JxxD	Wolfspeed	18	6, 25, 70	60	0,25	40
Transistors in production in 2013 - 2018						
CGH800xxD	Wolfspeed	8	15 - 60	65	0,4	28
CGHV40320D	Wolfspeed	4	320	65	0,5	50
CGHV60xxxD	Wolfspeed	6	40 - 170	65	0,5	50
TGF293x	Qorvo	25	2 - 11	50	0,15	28
TGF295x	Qorvo	12	7 - 70	55	0,25	32
CHK901x-99F	UMS	12	55, 85	50	0,25	30
CHK8015-99F	UMS	18	20	68	0,25	30
AMxxxWN	AMCOM	15	2 - 40	50	0,25	28
RT10-RT70	Резонанс	15	5 - 35	45	0,25	28
TA284 (разр)	Светлана-Рост	6	15	--	0,5	28
WP48xxxxxx	WavePia	5-10	15 - 340	--	0,45	48
WP28xxxxxx	WavePia	15	15 - 60	--	0,25	28

Structures of amplifying elements (cascades) of ultra-broadband amplifiers may be divided into three classes: hybrid-integral (HIC), monolithic-integral (MMIC) and quasimonolithic (QMIC) circuits; their main properties are shown in Table 3

Table 3

Parameters and characteristics	HIC	MMIC	QMIC
Dimensions	large	small	small
Customizability	yes	no	limited
Components cost	low	low	high
Lumped parameters elements implementation option	no	yes	yes
Active elements	discrete transistors	Integrated transistor structures	discrete transistors
Practical frequency use limit	12 GHz	Unlimited	14 GHz
Parameter development costs	low	high	medium

The choice of the amplifying elements design is made evaluating the specifics of the ultra-broadband amplifier requirements, the estimated production volume and development costs. From the point of view of circuit design, most ultra-broadband amplifiers (referring to terminal amplification stages) are manufactured in three principal versions: balanced amplifiers, multi-stage amplifiers with direct connections and amplifiers with distributed amplification.

Among the advantages of balanced circuit, widely used in HIC amplifiers, are good matching of input and output, low frequency response unevenness, and improved stability. The disadvantages include the limitations of the frequency band imposed by the dimensions and complexity of the quadrature bridges, the large dimensions of the cascades. The parameters of such amplifiers substantially depend on qualification of ultra-wideband quadrature bridges designers; the overview of design of such devices is presented in paper [2].

The summarized parameters of GaN amplifiers with distributed amplification of operation frequency range of 2-18 GHz available on the market are given in Table 4. The output power and efficiency of the amplifiers correspond to gain compression of 3-5 dB relative to the conditions of linear mode, which is typical for all types of GaN amplifiers.

Table 4

MMIC type	Manufacturer	Pout, W	Linear gain, db	Effeciency, %	Uc, B
NC11647C-218P2	METDA	2	11	10 - 15	28
ASL 4046	Aelius	3	9,0	13 - 20	25
CMD-184	Custom MMIC	3 - 5,5	13	--	28
TGA2214	Qorvo	5 - 6	22 - 25	22	22
HMC1087-Die	Analog Devices	8	11 - 12	20 - 24	28
NC11651C-218P8	METDA	8	12	20 - 25	28
GNM-2203	SIWI	9	9	22	28
TGA2573	Qorvo	10	9	22 - 30	30
NC11688C-218P10	METDA	10	20	20	28
NDNC01056	NEDITEK	10	12	20	28

Among the obvious advantages of amplifiers with distributed amplification circuits - very wide potential operating frequency band, good matching of input and output, and low frequency response unevenness. The main disadvantage is the relatively low efficiency, the problem is being solved by the best foreign specialists in the microwave microelectronics field. The minimum efficiency factor in the frequency band of the added power of 20% is a very good result for amplifiers of this class.

Reactive matching amplifiers, including (as a special case) multi-stage amplifiers, are most common among HIC, MMIC, and QMIC power amplifiers, including those with an ultra-octave band.

In this case, the electrical characteristics are achieved by improving output matching circuit and transformation of the standard wave impedance of the path (50 Ohms) to the optimal loading impedance of the output transistor (or a line of in-phase excited transistor structures), which ensures maximum output at all frequencies of the range, or maximum efficiency, or required compromise between these parameters.

In theory, such construction design should provide the best energy characteristics, and that is true for narrow-band and sub-octave amplifiers. However, the advantages for ultra-broadband amplifiers are not as significant, as shown in Table 5. The Table displays the parameters of the industrial MMIC ultra-broadband amplifiers of the 6-18 GHz band, constructed as per multi-stage reactive matching schemes.

Table 5

MMIC type	Manufacturer	Pout, W	Linear gain, db	Effeciency, %	Uc, B
TGA2501	Qorvo	2,5	26 ± 2	18 - 30	8
[3]	(2017)	6 - 10	11 - 15	17 - 27	8
GNM2305	SIWI	5	16	18	8
NC116137C-618P6	METDA	6 - 8	28 ± 3	22 - 25	28
NC11669C-618P10	METDA	10 - 16	20	20 - 25	24
TGA2963	Qorvo	20 - 35	32 ± 4,5	20 - 28	22
[4]	(2017)	16 - 20	12 ± 1	22 - 40	24
[5]	(2018)	30 - 53	17 - 25	13 - 30	25

The parameters of the three types of MMIC, constructed using GaAs pHEMT technology with power of 2.5-6 W, are compared in the Table. It is clear that the efficiency of these devices is 3-5% (only) lower than that of GaN amplifiers. It should also be noted that the area of the GaAs MMIC crystal is 16-32 mm2, while GaN amplifiers of the same power fit on the crystal area of 5-6 mm2.

With high gain and high output power (2–3 times greater than that achieved in traveling wave amplifier circuits), multi-stage ultra-broadband amplifiers based on reactive matching circuits have two serious drawbacks: high frequency response unevenness (2-3 dB per cascade) and high VSWR of output, greatly complicating the use of such MMIC. At the same time there is no noticeable improvement in the achieved efficiency values in comparison with the GaN traveling wave amplifier schemes.

4. Special aspects of ultra-broadband amplifiers circuitry design

The traditional and sufficiently well-studied method for improving efficiency of narrow-band amplifiers is (in general) the method of load control at harmonics of the main frequency [6]. Until 2009 the problem of expanding the frequency band of the amplifier while maintaining the option of optimal control of the harmonics loads was considered insurmountable. However, the authors of an article published in 2009 [7] charged at the low efficiency of the ultra-broadband amplifiers, proposing to use the principle of combination of well-known high-performance gain modes that smoothly transition from one to another with increase of frequency.

It should be noted however that significant results (Table 6) were obtained for single-stage reactive matching circuits and for relatively low frequencies (up to 2.5-4 GHz), at which the intrinsic reactivities of high-power GaN transistors still allow them to demonstrate the properties of ideal wrench, required for the implementation of highly efficient nonlinear vibration modes. At higher frequencies, the improvement of ultra-broadband amplifiers parameters is so far not so great.

Table 6

Publication	Type of used transistor	ΔF, GHz	Pout, W	Standard efficiency, %	Power Added efficiency, %
[7]	Cree, 10W	1,4 – 2,6	10	60 - 65	50 - 60
[8]	CGH60015D	0,4 – 4,1	10 - 16	40 - 62	38 - 58
[9]	CGH40010F	1,4 – 2,5	12 - 18	68 - 82	65 - 80
[10]	CGH40120F	0,6 – 2,6	80 - 115	49 - 65	44 - 55
[11]	CGH40025F	0,2 – 1,8	16 - 32	--	60 - 82

One of the effective ways of ultra-broadband amplifiers construction is the use of antiphase power dividers (bridges) and stacked transistor structures to increase or decrease the optimal load impedance, which in some cases allows to not utilize reactive elements and transformers that limit the frequency band in the output matching chains. This technique was used [12] to summarize four 25-Watt integrated GaN MMIC s, whereas the amplifiers designed to operate in a 50-Ohm path were paired in parallel, and the required 25-ohm impedance was reached by a coaxial antiphase bridge on ferrite core. Such solution allowed to obtain the output amplifier power of 94 to 142 W with a drain efficiency from 41 to 74% in the frequency band of 0.1 - 1.8 GHz.

5. Characteristics of modern ultra-broadband amplifiers

The overview of modern technical level of ultra-broadband amplifiers, by the example of parameters of solid-state amplifiers operating in the frequency ranges of 2-18 GHz and 6-18 GHz is presented in Table 7.

Table 7

Amplifier type	Manufacturer	ΔF. GHz	Pout, W	Gain, dB	ηa, %	Volume cm3
MPH020180G5041	Meuro	2 - 18	13	50	--	187
AMP1070	Exodus	2 - 18	30	50	5,2	552
RFLUPA0618GC	RF Lambda	6 - 18	20 - 40	56 - 62	6,2	889
PA1062	Mitron PTI	6 - 18	40	46	7,4	1134
RCA60180H46A	RFCore	6 - 18	40 - 45	29	5,0	31400
AMP1122	Exodus	6 - 18	100	60	7,8	1846
L0618-50-T523	Microsemi	6 - 18	100	55	--	3934
MPH060180G5053	Meuro	6 - 18	200	50	--	10080

6. Conclusion

The modern transistors and gallium nitride-based MMIC technologies allows the production of amplifying elements with a super-octave band and output power of more than 100 W with efficiency of 40-60% in the decimeter range, and more than 20-30 W with an efficiency of 20-30% in centimeter range. Solid-state power amplifiers of the 6-18 GHz range gradually occupy the traditional niche of the traveling wave tubes of the 100-Watt class. That said, the hardware efficiency of products of all categories leaves much to be desired – for example at least the 1-kilowatt power supply is required for operation of the 40-Watt amplifier.

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