SOLID STATE RF AMPLIFIERS FOR ACCELERATOR APPLICATIONS

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Abstract

Solid state RF amplifiers are being considered for an increasing number of accelerator applications, both circular and linear. Their capabilities extend from a few kW to several hundred kW, and from less than 100 MHz to above 1 GHz. This talk describes the basis principles of the main components, the evolution of the technology and gives the state of the art and future prospects of RF power amplifiers for accelerator applications.

THE SOLID STATE TECHNOLOGY

Solid state (SS) amplifiers are based on transistors instead of vacuum electron tubes as active device. First RF silicon devices were bipolar junction transistors (BJT) which were affected by thermal runaway and by secondary breakdown, respectively leading to temperature compensated bias circuits and reduced safe operating areas. Vacuum electron tubes were then generally preferred for medium and high power applications and solid state amplifiers were mainly used as driver stages with output CW power up to some hundreds watts at few tens of MHz.

With the development of the integrated circuit technology, the Metal Oxide Semiconductor Field Effect Transistor (MOSFET) could be manufactured (1963, Bell Laboratories, Atalla and Khang). It's worth to remind that the Mosfet conceptual design (1925, patent 1933 Julius Edgar Lilienfeld) is anterior to that of the BJ transistor (1948, Bell Labs William Shockley)! Contrary to BJTs, Mosfets don't suffer of the already quoted problems and have higher gain, lower noise and stand higher VSWR.

Vertical Mosfets (VMOS) were introduced in the 70's and UHF low power applications begun since the 80's and finally Double Diffusion Mosfets (DMOS, ST) and Lateral Diffusion Mosfets (LDMOS, Motorola), appeared in the 90's.

Since the beginning, the RF power solid state technology has been strongly boosted by several applications, mainly divided in five big fields:

- Non cellular radio communications (7.2÷13.6V)
- Avionics & Radar (14V÷36V, communication, navigation, radars, weather systems, etc),
- Wireless Infrastructures and FM/TV Broadcast (28÷50 V),
- ISM (≥50 V, Industrial (plasma generators, CO2 laser) scientific and medical (IMR, 10÷600 MHz)),

which continually contribute to increase performances while reducing costs. This trend is going on with the digital modulation which imposes a new challenge with higher linearity due to the very high peak to average power ratios involved.

Costs have been reduced by improving the silicon wafer sizes from 5", to 6" and 8", by optimising the manufacturing process, and, more recently, by increasing the thermal conductivity of the plastic housing, which is much less expensive than the ceramic ones. Performances have been improved by integrating electrostatic discharge (ESD) protections, increasing gain, efficiency, breakdown voltages and thermal stability.

Today, several transistors cover the bandwidth from few MHz to several GHz, delivering average power around hundreds of watts in CW mode and pick power reaching 1 kW in pulsed mode.

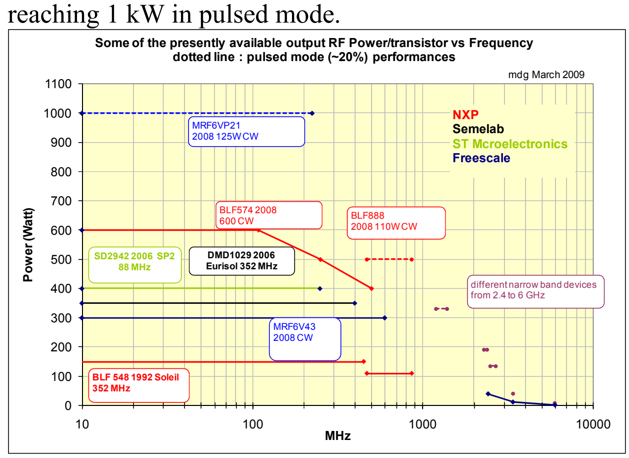


Figure 1: Available output RF power / transistor

Device working at drain bias around 100 V are available below 150 MHz, 50 V devices are available up to frequencies around 1 GHz, 28 V at higher frequencies, up to several GHz where GaAs dominate but where a new technology seems very promising: GaN, coupling the high frequency capability of GaAs and the high power and voltage capabilities of Si LDMOS.

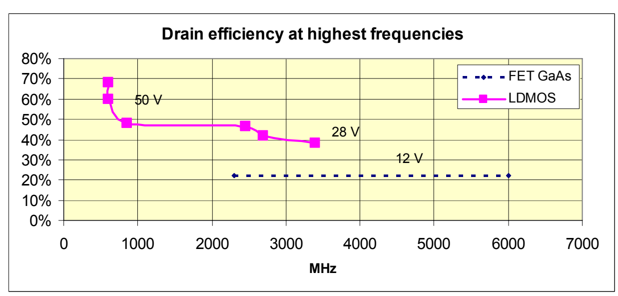


Figure 2 : Present limit of the LDMOS technology

RF power Mosfet manufacturing process

RF power mosfets are integrated circuits with a Small Scale Integration (SSI). The present technology uses 6" and 8" silicon wafers, from 0.1 mm to around 0.25 mm thick, on which some thousands of devices are diffused. The diffused wafer is then sawed and the different silicon chips ("dice") are separated. Each single die is then picked and placed on its package flange and connected to the external terminals via Au or Al wires (wire bonding) whose diameter is of few tens of microns.

Figure 3 : manufacturing phases

A protective lid is finally placed on top for mechanical protection. The housing participates in dissipating power loss, and then its thermal conductivity is a main issue.

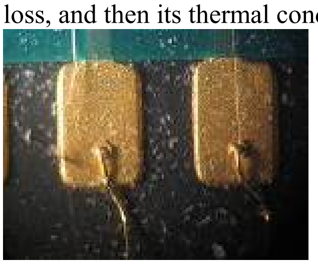


Figure 4 : wire bonding

Figure 5 : assembled die

Ceramic packages are still used at highest available power but they are being replaced by plastic ones (overmolded or air-cavity), whose thermal conductivity and temperature limit have been dramatically improved since a few years.

SOLID STATE AMPLIFIER ARCHITECTURE

RF Mosfets have very low input and output impedances which don't let direct paralleling of several transistors.

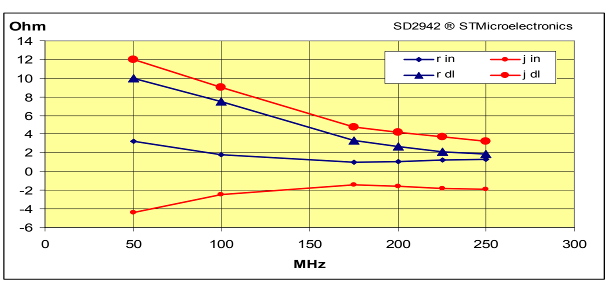
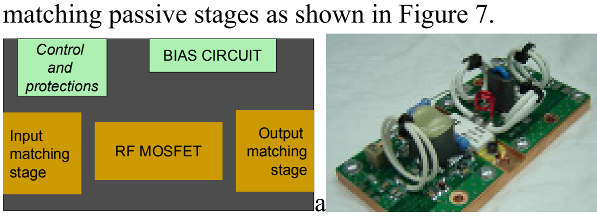


Figure 6: I/O typical impedances vs frequency

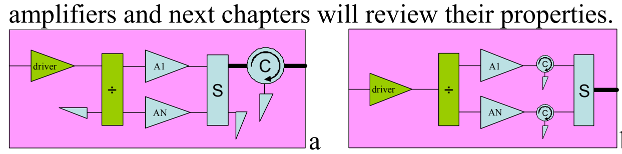
In most cases, the elementary RF brick, called pallet, is then based on 1 or maximum 2 transistors, mounted on a highly conducting metallic ground plane and equipped with their biasing network and with input and output matching passive stages as shown in Figure 7.



a b

Figure 7: a) typical pallet block diagram and picture

Several of these blocks are then combined together to obtain higher output power, in the best arrangement to fit the amount of power required by each application. Isolated dividers and couplers (Figure 8a) can be used to avoid oscillations or other phenomena which could bring to the transistor destruction. Circulators can also be used to decouple each amplifier, making it unconditionally stable, and in this case non isolated splitter/combiners can be used (Figure 8b). Splitter/combiners and circulators are therefore extremely important elements of solid state RF amplifiers and next chapters will review their properties.



a b

Figure 8: 2-way possible combining schemes.

Once a great amount of power has been collected from smaller devices, proper management of this power is very important, especially when it is reflected and has to be redistributed to all the contributors. In principle power combiners become splitters when used backward but, due to improper matching, the whole structure can become significantly asymmetrical and reflected power higher than generated has to be handled by each pallet. Circulators loads have then to be carefully dimensioned in case b), while big circulator and dummy load are required at the end of scheme a). Linear amplifiers helps in keeping the right matching at any power level, their output impedance being more stable than in class C.

At very low frequencies, circulators can't be used and transistors are operated at around 50% of their possibilities.

In case of failure of a few transistors, the solid state architecture grants significant amount of power being still available. In principle, in well designed systems, it is even possible to replace the broken module without interrupting the amplifier operation. In practice this characteristic is strictly linked to the power supply architecture and mechanical layout.

Another important point of the amplifier reliability is the computer control. A huge number of transistor current and interlock conditions must be monitored and localised for fast troubleshooting. First systems used analogical acquisition of all parameters eventually multiplexed. More recent solutions (PSI, Spiral2) use digital coding at the front end level and data communication by fieldbus.

SPLITTER/COMBINERS

Two kinds of devices are used to distribute or sum up RF signals. All of them are passive, multiport, reciprocal and the same device can be used to divide or combine signals. All of them are based on quarter wave sections of transmission lines and are narrow band, even if some tricks exist to wide the operating bandwidth. At lower frequencies, they can be realised with lumped elements too.

The simplest way to split/combine signals is the "y junction", so called from the shape it assumes in the 2-ways configuration. It can be built in the two different schemes presented in Figure 9, well adapted to coaxial lines and to striplines or microstrips

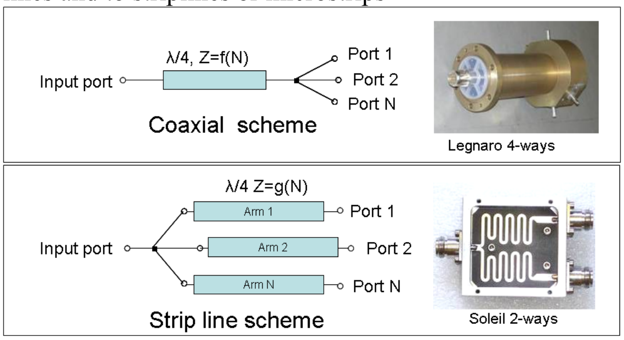


Figure 9: non isolated splitter/combiners

The common arm length and Zc have to be calculated to match the characteristic impedance. This solution has the advantages of requiring no resistors and in phase signals, but doesn't isolate the ports, whose impedance depends on the matching conditions on the other arms. It can be used only with unconditionally stable amplifier modules, embedding circulators to decouple direct and reverse powers.

Isolated combiners use one or more resistors to absorb non combined power. The resistor can be embedded in the network as in the Wilkinson (Ernest J.,1960) case of Figure 10a.

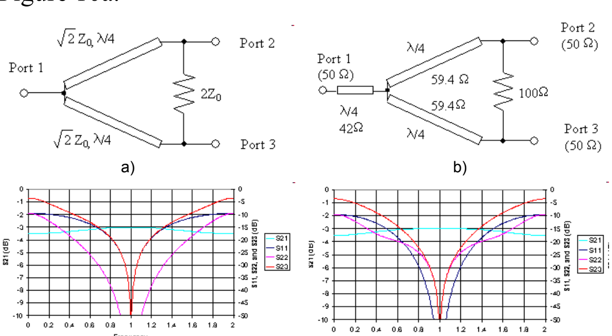


Figure 10 : 2-way Wilkinson (© Microwave101.com)

It has no effect on in-phase and equal amplitude signals but allows the 3 ports to be matched while isolating ports 2 and 3 for different values of phase or amplitude. The simplest configuration bandwidth is very narrow but it can be enlarged by placing a transmission line section on the input arm as shown in Figure 10b.

In a Wilkinson splitter, the resistor is embedded into the network, and must provide a short phase length for the scheme to work. At high power or frequency, the Gysel combiner is preferred.

The terminations in a Gysel are equal to Z0, and can be high-power loads. They can be external to the power splitter as any length of Z0 transmission line can be added between the loads and the splitter. It is also possible to measure the two resistors in parallel, even if they are grounded to the substrate. The Gysel scheme is largely used for N-way combiners in the 80 to 200 MHz range of frequency, avoiding the use of circulators on each pallet. It can be easily realised in microstrip or in-air structures, as shown in figures 11 and 12.

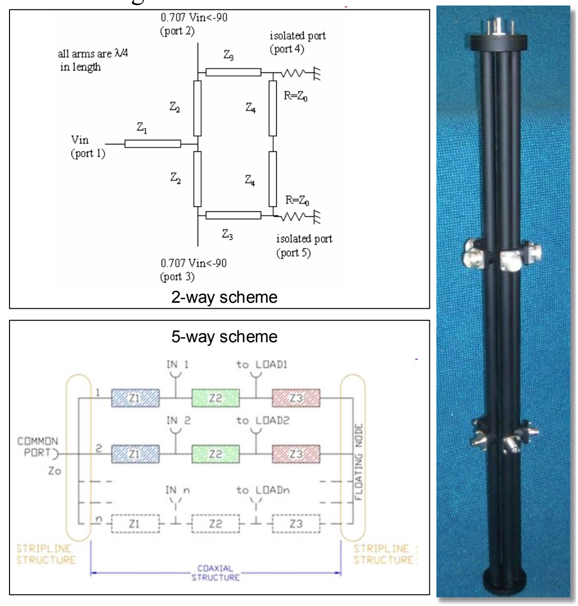


Figure 11 : Gysel combiner 2.5 kW, 211 MHz (© RES INGENIUM)

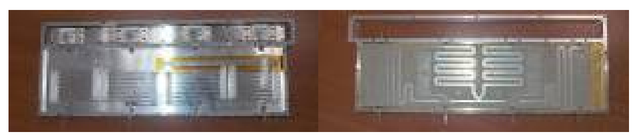


Figure 12 : Gysel combiner, 3 kW, 88 MHz (© DB Elettronica)

Another way of obtaining an isolated 2-way combiner is to use a quarter-wave coupled line coupler (directional coupler).

Figure 13 : coupled line combiner (© DB Elettronica)

CIRCULATORS

Circulators are passive, multiports, non reciprocal devices transferring the power from one port to another in a prescribed order. 3-port circulators are the most common in accelerator application.

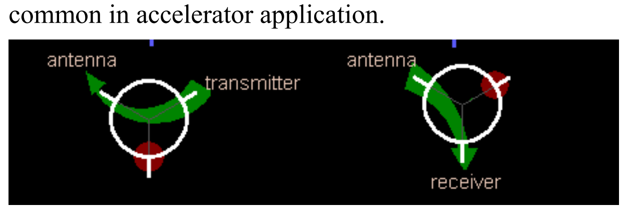


Figure 14 : diplexer application (© Microwave101)

After the basic work from Tellegen in 1948 on gyrators as a new network element and D. Polder in 1949 about the theory of ferromagnetic resonances, Hogan in 1950 invented the "Microwave Gyrator" at the Bell Laboratories.

Circulators are used as duplexers in broadcast and radar systems where the same antenna is coupled to a transmitter and a receiver (Figure 14) or simply as isolators when the signal coming back from the antenna is deviated on a dummy resistor. This is the configuration used in solid state amplifiers to protect the transistor or all the amplifier devices against reflected power.

Several circulator types exist but the junction one is the most commonly used as it can be implemented on strip (low power) or in-air (high power) lines as well as on waveguides. When using coaxial connectors, the 3-plate configuration shown in Figure 15 is normally used, where two plates of ferrite are put between the inner and outer conductors.

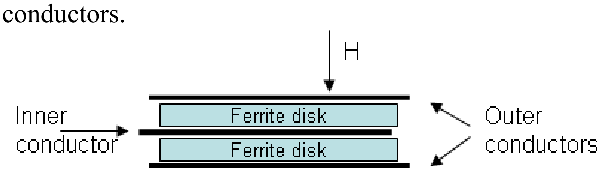


Figure 15 : 3 plate circulator principle (©Valvo GmBh)

The line entering each port is split in two equal branches going the other two ports (120° symmetry). Due to the interaction with the magnetised ferrite, the split entering waves at port 1, have different speeds such as they are in-phase when they arrive at port 2 (where they recombine) and in opposite phase at port 3 where they cancel.

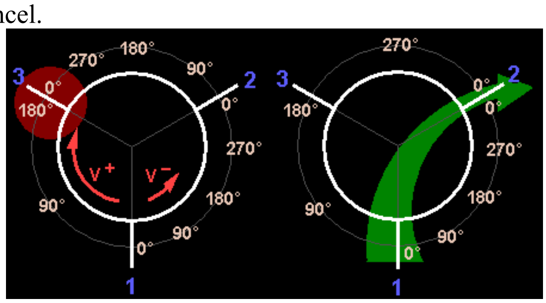


Figure 16 : circulator principle (courtesy)

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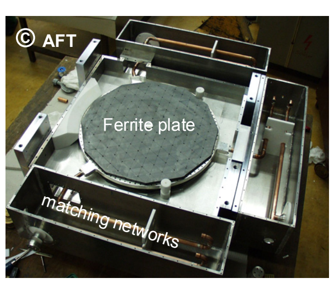


b

Figure 17 : 3 plate circulators, medium and high power examples.

Two different magnetisation levels ca be conveniently applied, one corresponding to anticlockwise path, the other to the clockwise one. This two levels are above and below the ferrite resonance value. The first one is mainly used at lower frequencies, the second at higher frequencies (>1.5 GHz). Examples of medium (up to 500 W) and high power (up to several tenths of kW) devices are shown in Figure 17.

ACCELERATOR APPLICATIONS

Solid state drivers up to 500 W, CW, have been intensively used in ion machines at frequency below 100 MHz. At higher frequencies or power levels, significant applications probably started in 1984 at SLAC, where a 400 W pulsed driver for a 2.856 GHZ klystron was installed or in 1986 at KEK, where the DTL of the proton linac was driven by a 2.5 kW pulsed amplifier, working at 201 MHz, slow duty cycle. Both projects used NPN BJTs developed at that time for space military application. In ‘94, CERN and GSI developed high duty cycle (60%) pulsed power with amplifiers up to 2.5 kW, working at 101, 108 and 202 MHz. Another important example of BJT application is the 805 MHz, 5 kW master oscillator amplifier operated at Lansce since ‘95.

A few years later (1997), Ti Ruan began the challenging adventure which led to the commissioning of a 352 MHz, 190 kW, CW amplifier for the Soleil synchrotron (France), in 2005. Soleil has been the first new machine choosing the SS technology since the beginning, as a solution to the lack of power sources really adapted to their power level requirements. One 35 kW amplifier and four 190 kW amplifiers are presently running, with a transistor failure rate of 3-4%.

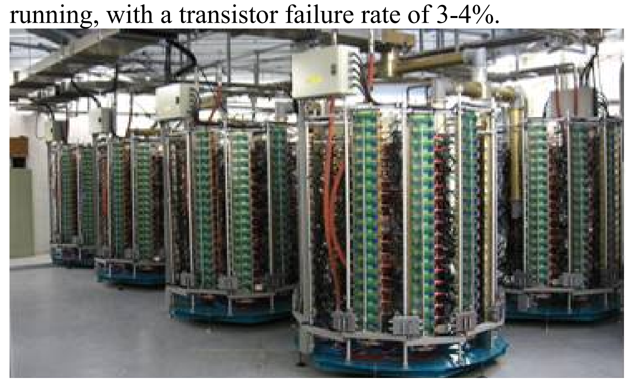
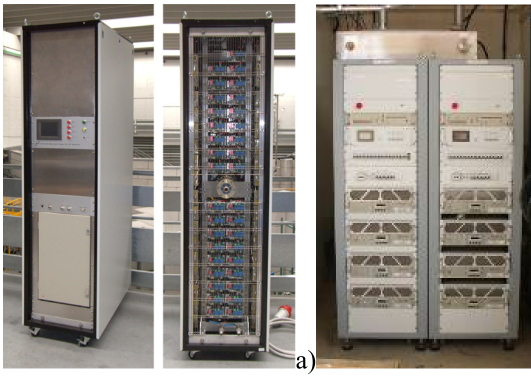


Figure 18 : Soleil amplifier room

In 2001, a klystron SS driver at microwave frequencies: 2.856 GHz, 300 W pulsed peak power was built in China to be used on the HLS light source injector.

In the framework of the Eurisol conceptual and design studies (2002-2009), INFN Legnaro has developed à 352 MHz, 20kW design oriented to SC proton linacs. Soleil and Legnaro amplifiers are based on unconditionally stable modules combined with non isolated splitter combiners. The two designs differ in the mechanical and power supply architectures as they are optimised for high output power (50 and 200 kW) in the first case and for 10 kW in the second one.



a) b)

Figure 19 : a) Eurisol 10 kW (352 MHZ) and b) Spiral2 20 kW (88 MHz), CW, power amplifiers.

The feedback of years of operation is very positive in most of laboratories: lifetime of more than 80000 hours at Los Alamos or Cern, with practically no transistor failure and a failure rate of a few percentages only, registered at Soleil where almost 1 MW of SS power is installed. Fan problems seem to be the most frequent troubles.

In 2005, for the Spiral 2 high intensity, ion superconducting linac (independently phase cavities) the SS technology was chosen, in a range of power levels (3kW to 20 kW) where grid tube devices still exist. Several tenths of independent amplifiers, designed and manufactured by commercial companies are going to be installed representing total RF power of 360 kW.

More and more labs all around the world, some of which reported in Table 1, have replaced, or plan to replace, some existing electron tube amplifier with SS ones. Future projects like FRIB, HIE ISOLDE and EURISOL at least, already foresee to install SS amplifiers; the installation of SS amplifiers for 1.6 MW, working at 176 and 352 MHz, up to 25 kW each, is foreseen for EURISOL,

Table 1 : List of some applications of solid state amplifiers in different laboratories worldwide.

YEAR	LAB	device	die tech	MHZ	kW - δ	kW CW	application
1986	KEK	2SC3286-M	NBN BJT	201	10		DTL in the KEK 40 MeV proton linac
1994	GSI/CERN	blf278	VDMOS	101, 108.4, 202	2.5 - 60%		GSI and CERN unilac injector
1994	LANL	MRF 141G	VMOS	201	5.5 - 18%		LANSCE DTL tetrode drivers
1997	LURE	blf548	VDMOS	352	1,5		driver for SuperACO RF system
1997	LANL	MRF899	BJT	805		2.8	LANSCE RF master generator amplifiier
1998	KEK	2SC3286-M	BJT	201	20 - 0,1%		debuncher in the KEK 40 MeV proton linac
2002	Germany			160	4 - 0.1%		new SC injector linac for cooler synchrotron COSY
2001	China			2856	0,3 - 0.1%		driver for klystron in 200 MeV e-linac, injector of the Hefei light source
2004	Brazil	D1029UK	LDMOS	500		35	LNLS booster
2005	France	LR301	LDMOS	352		180	Soleil storage ring booster
2008	France	SD2942	VDMOS	88		20	GANIL/Spiral2 - SC ion linac
2007	Germany			1300	1		Elbe electron linac: 10 kW klystron driver or 200W buncher amplifier
2008	PSI	MRF6P3300H	LDMOS	500		4,5	SLS strage ring bosteer amplifier (**60 kW final goal**)
2008	CERN	MRF 151G		0,6- 6		9	CERN LAIR and J-PARK RCS : tetrode driver for ion synchrotron
2008	Brazil	LR301	LDMOS	476		2,2	500 MeV booster of LNLS light source (**50 kW final goal**).

CONCLUSION

Transistors, splitter combiners and circulators are the elementary bricks of SS amplifiers. Recently the technology has taken advantages of prodigious development of semiconductor devices in broadcasting and other industrial applications and today the whole range of frequency of accelerator applications is covered at very competitive prices and performances.

The amplifier architecture generally requires the use of circulators. These can be distributed at the output of each transistor, in which case they help making the elementary pallet more stable at any phase of VSWR, or concentrated at the output of the amplifier where they help protecting the combiners too from high VSWR.

Operating advantages of this technology are the absence of high biasing voltages and longer life times but some other points can be underlined which are very important too: easy and quick maintenance, possibility of reduced power operation in case of failure, and better fitting of different power levels inside the same project, with one elementary brick.

The technology is very robust and available even from small commercial companies, as it requires lighter infrastructures than required by tubes amplifiers. Reliable operation up to 200 kW at 350 MHz has been proved. Similar levels at 500 MHz are already planned.

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REFERENCES

The author mainly went through the papers on SS amplifiers available from the proceedings of conferences reported on the JACoW website.

A lot of information was also found on the web, from the main transistor manufacturer sites and from the Microwave and Wiki encyclopaedias.