Mini-Circuits

Turnkey Solid-State Amplifiers for ISM RF & Microwave Energy

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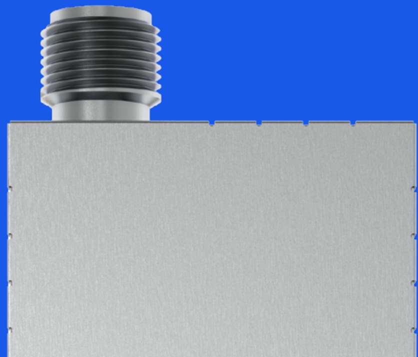

JULY 2021

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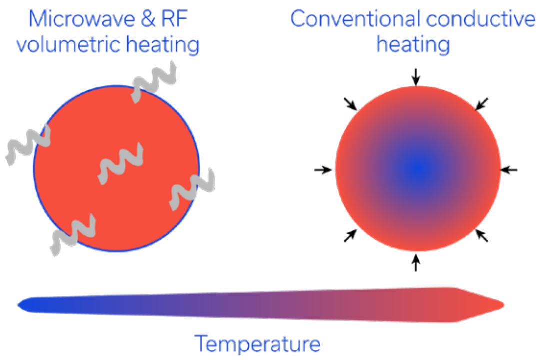
The Emerging Market for RF and Microwave Energy

While traditional RF and microwave applications are predominantly focused on wireless communication or navigation, recent advances in device technology have opened up an exciting range of non-communication, non-navigation applications of RF and microwave power. Dielectric heating is an important part of any RF and microwave heating process. Also known as electronic heating, radio frequency heating, or high-frequency heating, dielectric heating is the process by which alternating electromagnetic waves heat a dielectric material. Whereas conventional heating methods such as conduction or convection transfer heat from the surface of the material to the middle, RF and microwave heating heats the molecular structure volumetrically, throughout the whole material at once.

***Figure 1**: RF and microwave volumetric heating vs. conventional heating through conduction or convection.*



Using RF and microwave power to apply energy to materials is not a new concept, your household microwave oven being the most obvious example. But the magnetron tube used by the microwave oven to generate high-power RF and microwave signals has inherent constraints that limit its usefulness to more rudimentary, brute-force applications. The realization of RF and microwave energy through solid state technologies has enabled unprecedented control over frequency and power for more sensitive applications. This new precision allows the system to react to any changes in the load conditions in real time and in a smart way determined by the user.

Current RF and microwave energy applications are predominantly focused on the industrial, scientific and medical (ISM) frequency bands, shown in Table 1.

***Table 1**: ISM Frequency Band Definitions.*

Frequency	Wavelength
27.1MHz + 0.2%	11.06m
433.9 MHz + 0.2%	69.14 cm
915 MHz + 13 MHz	32.75 cm
2450 MHz + 50 MHz	12.24 cm
5800 MHz + 75 MHz	5.17 cm

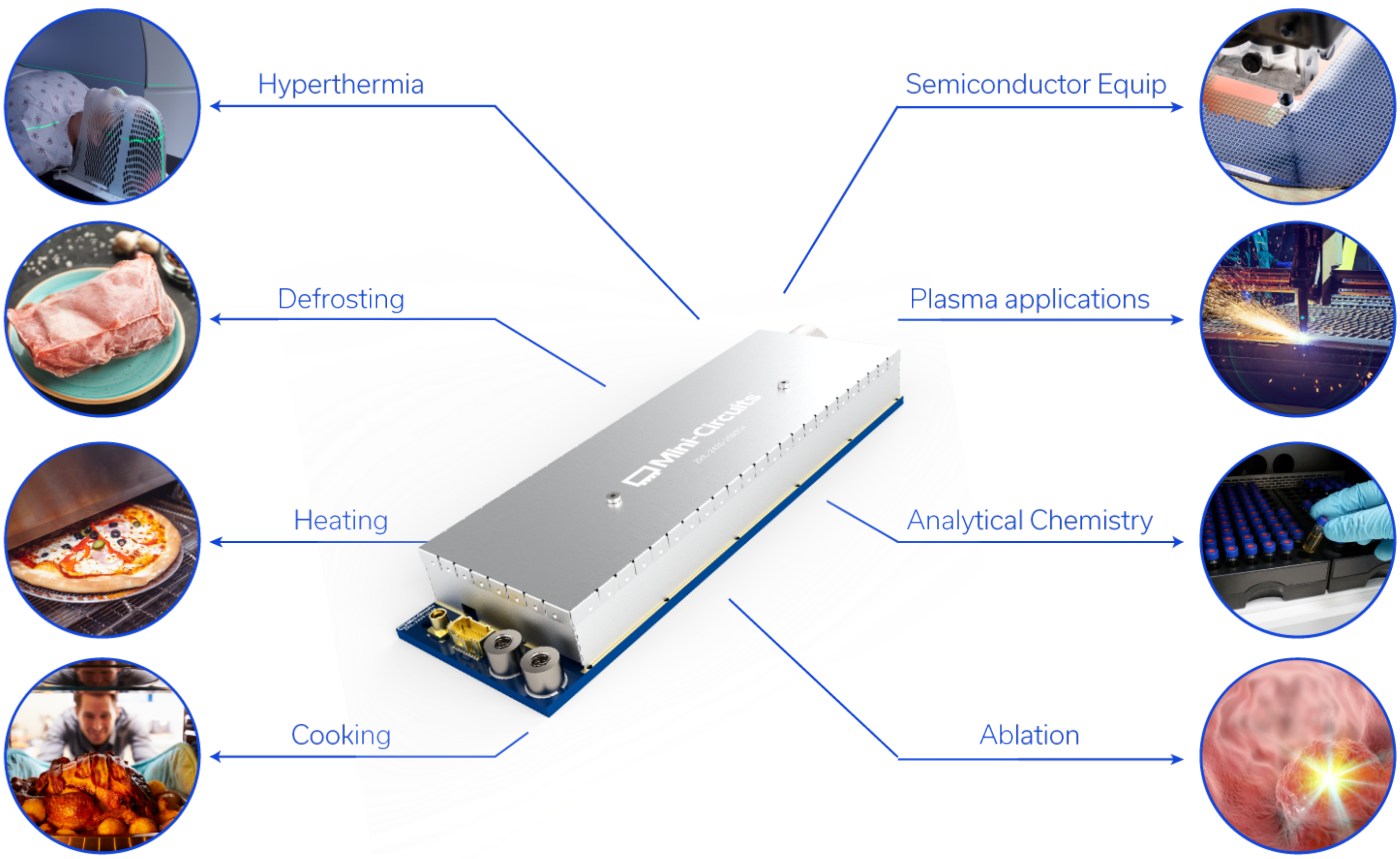
The open use of the ISM bands for many non-communication systems supports a diverse array of applications of RF and microwave energy, quite a few of which are already adopting solid state solutions to heat materials. Some of the applications are shown in Figure 2.

Additional emerging applications include:

- Pasteurization and other food processing
- Welding and materials processing
- Microwave-assisted chemistry: protein analysis, cell warming, etc.
- Plasma generation for semiconductor fabrication, RF-excited lasers, plasma lighting, and surface treatment
- Particle accelerators: electron, X-ray
- Medical: MRI, diathermy
- Various applications for sterilization and disinfection

These are just some of the areas where RF and microwave energy is being adopted, but many others exist, and the ultimate potential for this technology is only just being explored.

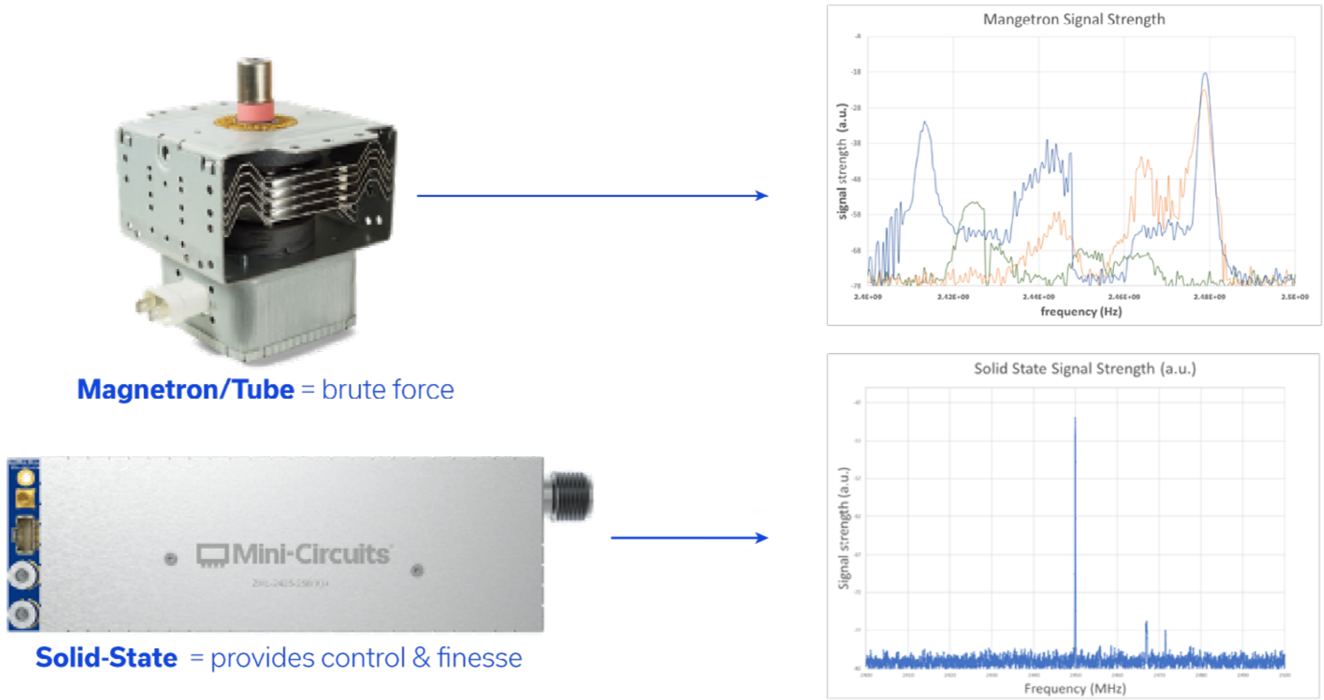
***Figure 2**: Typical Applications of RF and MW Energy.*



Current Technologies for RF & Microwave Energy:

Comparing Magnetrons with Solid-State

***Figure 3**: Comparison of the frequency response of three different magnetrons (top) to a solid-state amplifier (bottom).*



Until recently, applications for RF and microwave energy have been addressed mostly with magnetron generators and tubes. These solutions use RF and microwave power to heat a dielectric material, but are really brute force solutions with limited control. The magnetron, while practical for some applications, has many undesirable features. First off, as shown in Figure 3, the RF power from three different magnetrons illustrates the relatively noisy frequency spectrum of this technology, and the output frequency inherently varies as the RF power is increased. It requires voltage biasing in the order of kV to operate, and this is supplied by large power sources. Magnetrons have limited control mechanisms and can't easily be shut-off and restarted.

By comparison, the solid-state power amplifier solution can be controlled and tuned to a fixed, stable frequency, and an adjustable output power, thus providing focused RF and microwave energy exactly where it's needed. Other advantages include more efficient power delivery to the load as the system is constantly adapting to the frequency in real time. Solid state amplifiers have a small form factor and are modular, so they can be cascaded to produce higher output power. Finally, whereas magnetrons have limited control mechanisms, solid-state amplifiers can easily be powered down through feedback control, which we discuss in greater detail below.

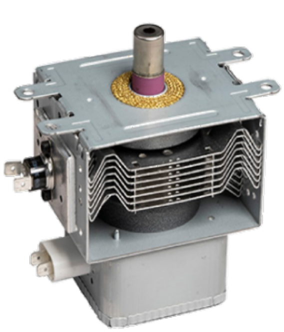
Table 2*: Feature by feature comparison between magnetron and solid-state RF and microwave energy technology.*

Feature	Magnetron	Solid-State
Frequency Control	No	Yes
Output Power Control	Limited	Yes, 0 - 100%
Automatic shut-down	No	Yes
Power Supply	kV range	30-35V
System Size	Large and heavy	Small and lightweight
Operating Life	1-1.5 years	10-15 years
Phase control	Complicated	Easy

Operating Life and Cost of Ownership

Solid state technologies have inherently longer mean-time-to-failure (MTTF) compared with other technologies, including magnetrons. As shown in Figure 4, the lifetime of a magnetron for industrial applications is on the order of a year, which means that the component must be frequently replaced. The lifetime of a solid-state amplifier, on the other hand, is on the order of 15 years. So, there are clear advantages from a cost perspective, as well as a reliability perspective, for replacing legacy magnetrons with solid-state amplifiers.

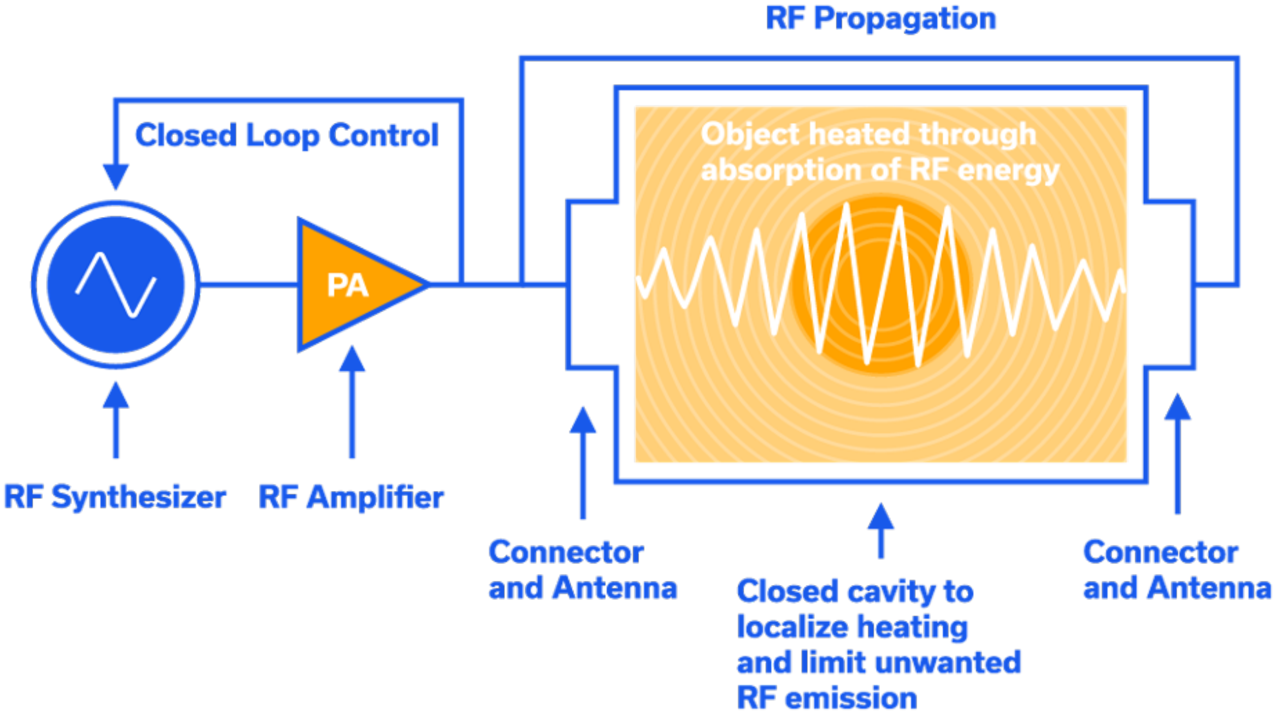
Figure 4*: Comparison of the Mean-Time-to-Failure (MTTF) of the magnetron to the solid-state amplifier.*



Feedback and Control

As we've mentioned, the power level and frequency spectrum of a magnetron can't be controlled, whereas for solid-state amplifiers, well-known RF techniques can be leveraged to provide precise control over both parameters. This capability is among the most powerful advantages of solid-state-generated RF and microwave energy. Figure 5 shows a simple block diagram of the control loop for a solid-state power amplifier used in a generic RF and microwave energy application. The solid-state power amplifier is heating two sides of a cavity and incorporates a feedback loop from the amplifier output to the RF synthesizer. Measuring the forward and reflected signal to and from the cavity, and using those measurements to automatically adjust the frequency and power from the source enables optimally efficient energy delivery to the target. This technique supports CW and pulsed power, allows the amplifier to adapt power to changes in the dielectric material in real time, and it permits fast automatic shutdown in response to potentially hazardous conditions.

***Figure 5**: Feedback Control Loop for the solid-state amplifier.*



Filling The Gap for a Turnkey Solid State Power Amplifier Solution

The advantages of solid-state solutions over magnetrons are clear at this point, and many customers are already in the process of transitioning, but several challenges remain for broader commercialization. Some customers have taken on the burden of designing and manufacturing their own solid-state amplifier modules, which requires extensive design expertise, development time and investment. Even for those with the means, this approach creates a tremendous diversion of resources away from the end system, inflates project costs and delays time to market.

For smaller customers with limited budgets and engineering staff, in-house development of solid-state power amplifiers is simply impractical. Outsourcing solid state amplifier development brings several challenges due to a nascent and still relatively limited supply base. Product quality and supply chain stability are both concerns with using smaller or lesser-known suppliers. Meanwhile, some solid state power amplifier products have complex integration requirements, and suppliers don't offer knowledgeable engineering support for customers without dedicated RF expertise.

Mini-Circuits' new solid-state power amplifier line will fill these deficits in the market with cost-effective, turnkey solutions for ISM RF and microwave energy applications. All models include on-chip sensors for feedback that can be easily utilized in the overall system. These products offer industry leading ease of use and come backed by Mini-Circuits' reputation for quality, supply chain stability, and accessible, engineer-to-engineer application support.

The complexity of solid-state amplifier design is best supported by a highly experienced solid-state power amplifier design team. Mini-Circuits has built a team of some of the industry's most experienced power amplifier design engineers not just to develop the product line, but to collaborate with customers in solving problems.

Mini-Circuits Inaugural SSPA for RF & Microwave Energy: ZHL-2425-250X+

Design Overview

Mini-Circuits' inaugural solid state power amplifier for RF and microwave energy applications is the ZHL-2425-250X+. This model is connectorized, matched to 50Ω at the input and output ports, and has the capability to provide a maximum of 300W CW power over the 2.4 to 2.5 GHz ISM band. A simplified functional block diagram and the housing for the amplifier are shown in Figure 6.

The block diagram includes the RF detector, which measures the output power in the forward path and a second RF detector that measures the reflected power. A circulator is utilized to protect the amplifier module from any unwanted power seen on the output terminal. The control and monitoring circuitry block includes analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) allowing measured RF detector analog voltages to be read out in both the analog and digital domain, and provide a feedback loop to the controller through an I^{2}C connection with response times in the order of tens of microseconds.

The analog output buffers are shown on the right-hand side of the block diagram with the analog information that is available for the user. These can typically be used when faster feedback to the application is required.

The analog output voltage or the ADC output digital bits are available to the user to add intelligence through the overall feedback control loop to their own application controller. Alternately, Mini-Circuits provides an intelligent, easy-to-use controller and signal source solution (ISC-2425-27+) to work in conjunction with the ZHL-2425-250X+ and close that feedback loop as shown in Figure 7. Control signals received from the external controller are shown on the left-hand side of the control and monitoring circuitry block in Figure 6, while the user's specific application control is communicated through the I^{2}C bus. Also shown are the DC signals in the power amplifier that are monitored, including power supply voltage, power supply current, and the temperature sensor. The analog temperature sensor signal can be sent out to the external controller as an analog signal or as digital bits.

Figure 6*: ZHL-2425-250X+ package and block diagram.*

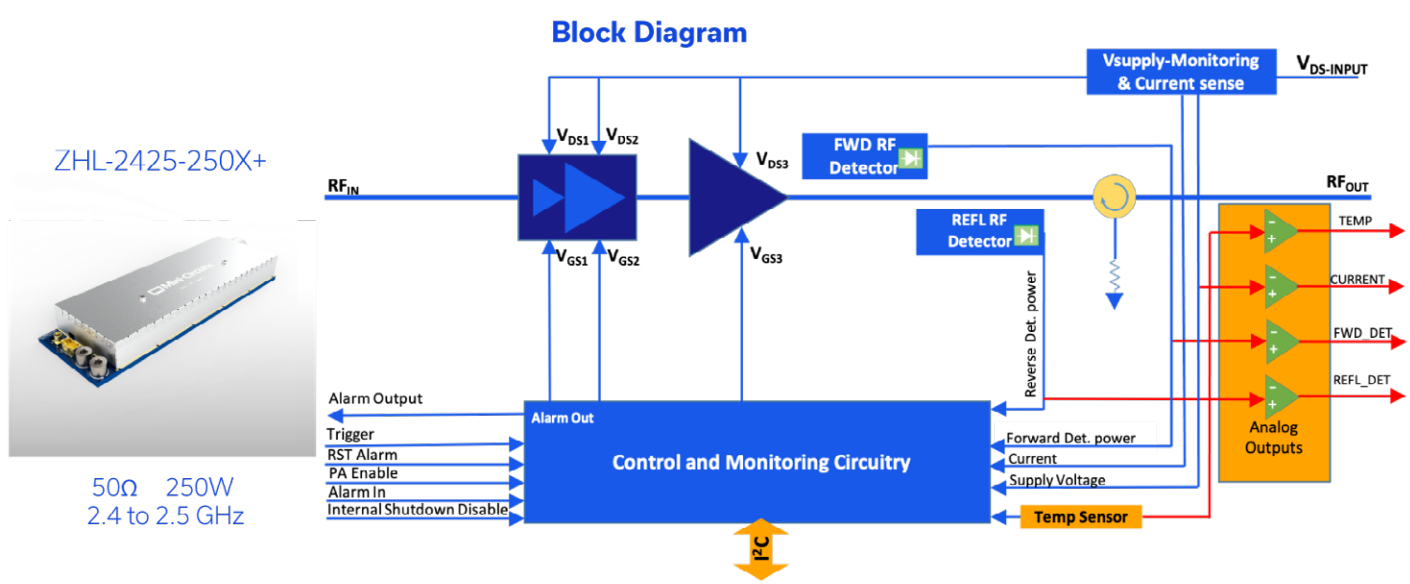
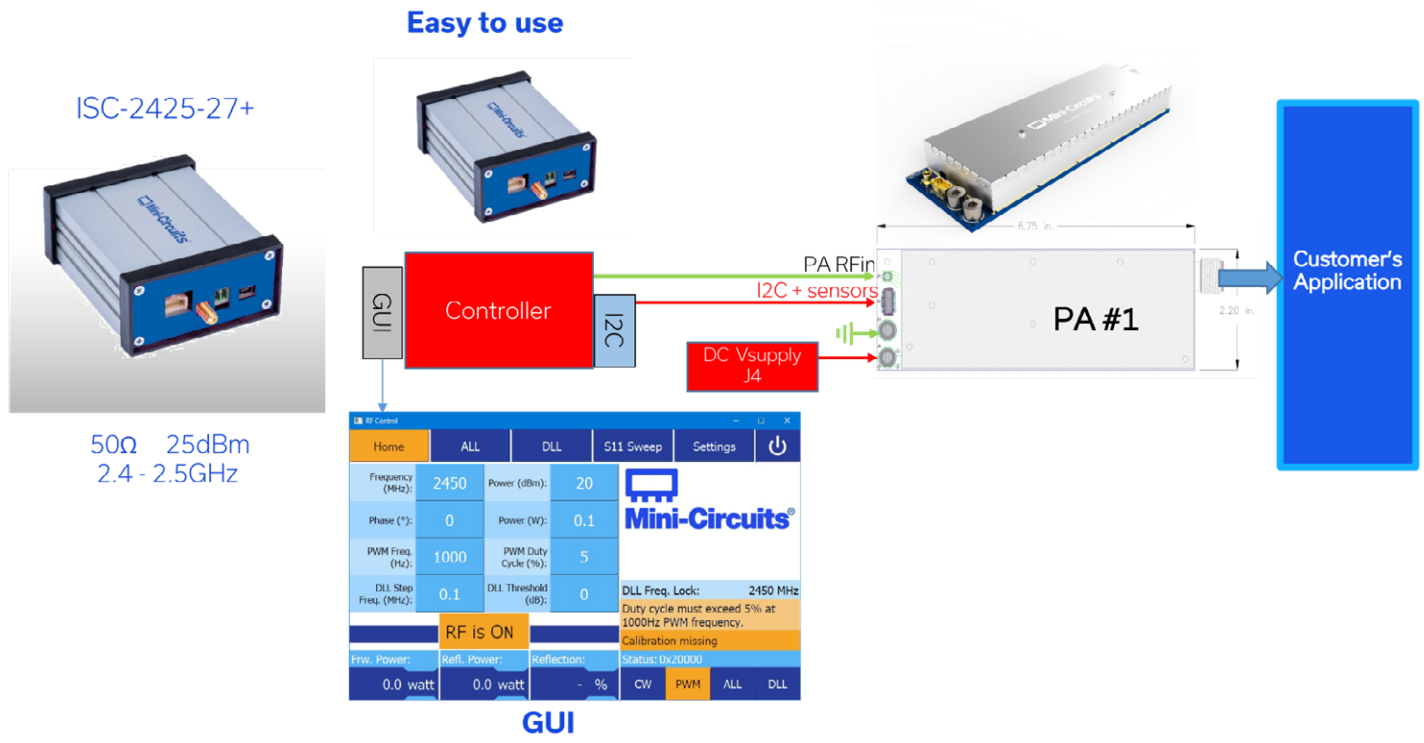


Figure 7: *Mini-Circuits system controller (ISM-2425-25+) and amplifier modules (ZHL-2425-250X+)*



Key Performance Features

The ZHL-2425-250X+ delivers CW power that can be regulated precisely from 1W up to 300W at P3dB. Built using high-efficiency LDMOS technology, the amplifier operates on a single 32V supply and provides 41 dB gain with a +14 dBm input signal as well as 60% power added efficiency (PAE) in most applications. This model features extensive built-in monitoring and protections for temperature, current, forward and reverse power, as well as automatic shutdown under hazardous conditions. It features mounting screw holes for either air- or water-cooling and comes in a compact, lightweight housing (55.9 x 171.5 x 15mm, 0.29kg) accommodating single or multiple unit integration in crowded system layouts.

For more details and complete electrical specifications, refer to the model datasheet.

The ZHL-2425-250X+ is currently one of three amplifiers in Mini-Circuits growing SSPA product line, with several others now in development spanning frequencies from 13 MHz to 5.8 GHz and power levels up to 25 kW and beyond. Learn more about the ZHL-2425-250X+ and additional models on our website at: https://www.mcdi-ltd.com/solid-state-power-amplifiers

Additional models in our portfolio will be discussed in subsequent articles.

Conclusion

Mini-Circuits has developed a robust, competitive turnkey solid-state amplifier solution for the RF and microwave energy market with the introduction of the ZHL-2425-250X+. The product gives users the peace of mind that comes with Mini-Circuits' 50+ years of experience supplying RF components and integrated modules. Mini-Circuits will continue to build off the success of the ZHL-2425-250X+ with the release of new products that support both higher power and other ISM band applications. Customers with specific requirements for solid state RF and microwave energy are encouraged to reach out to our team as our product development roadmap is planned based on current and future customer needs. Look for more exciting product releases coming soon as Mini-Circuits expands its RF energy product family.

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13 MHZ TO 5.8 GHZ | UP TO 1.7KW

Solid State Power Amplifiers

Turnkey ISM RF Energy Solutions from
the World's Trusted Partner for All Things RF

PLUG 'N PLAY

Leave the amplifier design to us and focus on your end system

MODULAR

Easy to scale to higher power levels

CONTROL

High-resolution frequency and power control at your fingertips

Next generation applications:

- Plasma Generation
- Dielectric Heating
- Industrial Heating & Drying
- Cooking
- Medical Technologies
- And Many More!

LEARN MORE

Preliminary Specifications:
Product specifications and features are subject to change without warning.

Mini-Circuits®

Amplifiers Available Now

2.4 TO 2.5 GHZ | 300W

ZHL-2425-250X+

- Suitable for CW and pulsed signals
- High gain, 40 dB
- High efficiency, 60%
- Built-in monitoring and protection for temperature, current, forward and reflected power
- User-friendly I2C control interface

27 MHZ | 1.7 KW

ZHL-0027-1K7X+

- Suitable for CW and pulsed signals
- 26 dB gain
- High efficiency, 80%
- Built-in monitoring for temperature and current
- Built-in emergency switch-off

27 MHZ | 75W

ZHL-0027-075X+

- 1 input to 4 19W output channels
- Suitable for CW and pulsed signals
- 16 dB gain at P3dB
- High efficiency, 55%
- Integrated harmonic suppression
- Temperature compensated gate bias

2.4 TO 2.5 GHZ | +25 DBM

Signal Generator and Controller ISC-2425-25+

- High-resolution control range of key RF parameters
- Freely programmable with comprehensive command language
- Embedded functionalities for end-user applications
- Standalone or multi-channel operation (coherent or incoherent modes)
- Easy integration with control protocols such as RS422 & RS485

Coming Soon!

ISM bands up to 5.8 GHz

10W to 25+ kW.

Preliminary Specifications:
Product specifications and features are subject to change without warning.

Mini-Circuits®

TESTING & SCREENING EEE-INST-002 COMPLIANT SPACE COMPONENT

IN-HOUSE SPACE UPSCREENING

Launch Prep

Mil-Spec or Equivalent Qualifications

- 30+ years of space-level screening and testing
- 7500+ components and custom capabilities
- EEE-INST-002 compliant workflows

Standard Capabilities

Burn-in, thermal cycling and shock, vibration*, radiographic inspection*, destructive physical analysis (DPA)*, mechanical shock, hermeticity with accompanying acceptance test procedure (ATP).

*While Mini-Circuits performs most of its testing and upscreening in-house, we use specialist partners for a limited selection of tests.

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