OBJECTIVE: Develop and demonstrate a highly efficient and compact continuous wave S-band magnetron source with a stabilized output capable of frequency shift keying over a narrow bandwidth.

DESCRIPTION: The generation of high continuous wave (CW) power at S-band frequencies is a common requirement in the field of industrial microwave heating. Magnetrons generating kilowatts (kWs) to tens of kWs are preferred sources for microwave ovens used in industrial food processing and for materials processing requiring rapid bulk heating. However, for such industrial uses, the quality of the generated microwave power is not critical. The frequency is not critical, noise is not an issue provided it does not interfere with nearby electronics, and the phase of the generated signal need not be controlled. Within these loose constraints, magnetrons have proven to be highly efficient and compact sources, often achieving efficiencies as high as 70% or more. Additionally, the conventional magnetron, among all vacuum devices, is exceedingly simple in design and construction, making it a cheap source of microwave power.

While modern radar and communications systems require far more sophisticated sources of microwave power, applications remain where the magnetron is still attractive. For example, radio beacons require relatively simple sources of CW power. Target emulators, which mimic threat sources for training or live-fire test purposes, and simple “fire and forget” jammers must be as cheap as possible since they are essentially disposable. However, even for these applications some control over the frequency, phase, and noise emitted by the source is required. A free-running magnetron simply will not do for many applications.

Stabilization of the magnetron frequency and phase as well as improved signal quality (reduced noise and spurious signal content) can be obtained by injection locking, where an external “locking” signal is injected directly into the magnetron output port. The injected signal serves to synchronize the otherwise free-running magnetron frequency and phase to itself, reducing noise in the process. In applications where the purpose is solely to reduce noise or combine the output power of multiple magnetrons, the magnetron output may (if suitably sampled, filtered, and adjusted in phase) itself be used as the injected signal. However, injection locking with an external source has also been demonstrated to provide sufficient control of the magnetron frequency and phase to make the device viable for some radar and communications functions. In fact, properly designed, an injection locked magnetron can be phase controlled and tuned across some small frequency band (typically a few MHz) such that coherency is achieved while simple modulations such as frequency shift keying and phase shift keying are applied.

Injection locking, though effective, introduces two complicating factors at the system level. First, since the interaction circuit of the magnetron is usually under-coupled to the output, a relatively strong locking signal is required. Therefore, the technique requires an external source of rather high power to generate the locking signal. This is especially true if fast frequency or phase modulation is required, as it has been shown that the ability of the magnetron to follow sudden changes in injected frequency or phase is proportional to the injected power level. Likewise, the total range of frequencies over which the magnetron can maintain lock is also dependent on the injected power. Second, the locking signal generator must be protected from the magnetron output power by a circulator. The injection signal generator, circulator, and associated circuitry therefore add weight, size, and cost to the overall system, somewhat defeating the purpose for which the magnetron was chosen in the first place.

The Navy needs a novel magnetron source for high power CW microwave generation at S-band frequencies. The source must be compact, efficient, and affordable. The source must be capable of fast tuning across a narrow band (at least 5 MHz) with a locked frequency response sufficient to support a data transmission rate of 2 Mb/sec using simple frequency shift keying (5 MHz excursion per bit). A wider narrow band frequency response and capability for other constant-envelope modulation schemes are desirable, with the figure of merit being the modulation bandwidth divided by the locking signal power required to maintain the desired 2 Mb/sec data rate. Broadband mechanical tuning (over at least 1 GHz) is ultimately desired but this need not be demonstrated for this effort. Rather, show broadband tuning need only as feasible. A minimum output power of 5 kW (CW) is desired, and the device may be demonstrated at any center frequency within S-band (demonstration in the 2.45 GHz Industrial-Scientific-Medical band is encouraged in order to take
advantage of the equipment available from the industrial microwave heating industry). The magnetron source may only use forced air-cooling (any volume and flow with inlet air assumed to be at room temperature and pressure).

The goal of this effort is to demonstrate the S-band magnetron source. However, the application is that of a compact and highly efficient transmitter and the magnetron should therefore be designed to minimize system weight, power consumption, and cooling load. Magnetrons are the most efficient, compact, and cost effective sources of raw microwave power available and it follows that an innovative technique for efficient and effective direct (i.e. without need of a circulator) injection locking of a highly efficient magnetron (meeting the requirements described above) would yield the lowest overall system size, weight, and power (SWaP). Therefore, an estimate of transmitter system SWaP is a requirement of this effort. Two figures of merit are relevant when comparing alternate technical approaches. The first is power density, defined as the output (CW) microwave power divided by the source weight (including power supply and any injection locking or other equipment required to make the source perform as required). The second is wall-plug efficiency, defined as the output (CW) microwave power divided by the total input electrical power (including any power consumed by the injection locking, power supply, and other equipment required to make the source perform as required).

To conclude the effort, the magnetron shall be tested to confirm that it first meets the modulation and power output requirements. The magnetron efficiency and cooling requirements shall then be determined. Finally, based on the demonstrated power and the observed efficiency, an estimate of the resulting SWaP requirements for the transmitter shall be derived, including estimates of power density and wall-plug efficiency. The low-SWaP transmitter need not actually be built and demonstrated, only validated through some combination of design and analysis.

PHASE I: Develop a concept for a compact and highly efficient S-band magnetron while meeting the minimum performance parameters detailed in the Description. Demonstrate the feasibility of the approach by some combination of analysis and modelling and simulation; and predict the ability of the concept to achieve optimized power density, efficiency, and affordability. The Phase I Option, if exercised, will include a device specification and system interface specification in preparation for device prototype development and demonstration in Phase II.

PHASE II: Develop and deliver a prototype compact CW S-band magnetron source that meets the requirements in the Description. Test and deliver the prototype to the Naval Research Laboratory along with a complete system interface description, performance specification, test data, and system SWaP estimate.

PHASE III DUAL-USE APPLICATIONS: Support the Navy in transitioning the technology for Government use. Since the prototype resulting from Phase II is a generic demonstration of the technology, assist in applying the design for specific system applications, such as expendable target emulators. Assist in scaling the device to different frequency bands and higher powers, and by implementing broadband tuning if required.

Since magnetrons already have many non-military applications (e.g., microwave heating, industrial materials processing), the technology resulting from this effort, being more compact and efficient, should find a ready application in these commercial markets.

REFERENCES:

KEYWORDS: Magnetron; Injection Locking; Frequency Shift Keying; Phase Shift Keying; Microwave Heating; Microwave