100 W Operation of a Cold Cathode TWT

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***Abstract*—Recent demonstration of low-voltage high-transconductance field emitter array operation holds promise for the successful development of reliable cold cathode vacuum electronics device technologies. This paper reports on the experimental studies of implementation of such field emitter arrays as the electron source for a moderate power traveling wave tube (TWT) operating in the C-band frequency regime. The cold cathode TWT has operated for over 150 h at duty factors up to 10%, beam currents up to 121 mA, and RF powers up to 100 W at 5 GHz. High cathode current densities of 15.4 A/cm^2 were achieved concurrent with excellent beam control, resulting in 99.4% beam transmission under zero-RF-drive operating conditions and 97.3% transmission at maximum RF output power. The cathode is shown to operate with a 72% reduction in the operating voltage from the previous generation of emitters fabricated by SRI International, bringing the operating voltage for full current operation well below 100 V. Extensive device characterization and life testing has been performed, and interesting variation in cathode performance was observed during the high-duty high-current portion of the testing program. The results presented here represent the highest current, highest power, and highest duty factor ever reported for an RF vacuum device employing a field emission cold cathode electron source.**

***Index Terms*—Cold cathode, field emitter array, microwave amplifier, traveling wave tube (TWT), vacuum electron device.**

I. Introduction

REPLACEMENT of the ubiquitous thermionic cathode used in virtually all RF vacuum electronics devices with the "cold cathode" has long held the promise of revolutionary advancement of cathode and RF performance in such devices, as well as the elimination of the many manufacturing challenges encountered with present-day thermionic cathodes and electron guns. Cold cathodes make possible high current density operation without the inherent life-limiting mechanism encountered with thermionic devices—this feature becoming increasingly important as compact high-frequency sources are further developed in coming years. Operation at room temperature eliminates the complex electron gun design and cathode manufacturing technologies required to heat the cathode to near 1000 °C while limiting the temperature rise and differential thermal expansion of surrounding gun material. Time scales for cold cathode turn-on from an OFF state to a fully-ON state are also decreased by several orders of magnitude as the thermionic cathode responds on thermal diffusion time scales of seconds while the cold cathode responds on voltage charging time scales of tens of nanoseconds. In addition, the voltage required for such beam modulation is reduced by an order of magnitude below that of an electrode-modulated thermionic gun. The importance of and benefit derived from these and other performance characteristics will depend on the intended application. Thorough discussions of the application of cold cathode technology to microwave devices can be found in [2] and [3].

Despite the potential benefits, the development of RF vacuum electronics sources and amplifiers exploiting the unique characteristics of the cold cathode has been limited. Programs at several institutions have attempted cold cathode operation in gyrotrons [4], klystrons [5], and traveling wave tubes (TWTs) [3], [6]–[8]. Though all of these programs used Spindt-type field emitter arrays [9] as the cold cathode electron source, development of other types of cold cathodes are actively being pursued, including carbon nanotubes, carbon nanosheets, and ZnO nanorods [10]–[12]. To date, however, only the Spindt-type cathodes have demonstrated the current densities and total currents required to achieve operation in 100-W-class RF devices. In addition, recent developments at SRI International have successfully reduced the operating voltage of their newest generation of field emitter arrays from several hundred volts to about 80 V, significantly reducing the electric field across the cathode substrate and along the internal cathode surfaces, potentially providing greatly improved cathode reliability and lifetime. To this end, the project reported here has the goal of evaluating cathode and device performance under conditions typically required in actual applications, including operation up to 100 W power levels and operation at high duty factors and over extended periods of time. This paper presents the experimental results of the first prototype of this program—a cold cathode TWT employing a newly developed low-voltage emitter, operating at duty factors, currents, and power levels surpassing those achieved by any previous field emission cold cathode device.

II. Experimental Hardware

A. TWT

The TWT developed for this program operates in the C-band frequency regime and was designed with operating parameters consistent with applications employing microwave power modules (MPMs) [13]. That is, the TWT is compact and operates

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