Microwave Readout Techniques for Very Large Arrays of Nuclear Sensors

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ABSTRACT:

We propose to develop an inexpensive yet powerful readout technique that will enable very large arrays of diverse sensor types for nuclear materials quantification and tracking. The readout technique that we will develop is based on microwave transmission and reflection. Sensing elements are coupled to simple microwave resonant circuits and the state of a sensor is probed using a microwave tone signal. Using standard lithography tools, thousands to millions of resonators can be straightforwardly fabricated, each with a unique, identifying resonant frequency. This approach is naturally compatible with frequency-domain multiplexing, thus allowing a large array of sensors to be probed using only two coaxial signal lines. The use of microwave techniques dramatically simplifies the packaging and interconnections required for large or distributed sensor arrays. However, this approach transfers complexity to room temperature electronics that must synthesize a microwave tone for each sensor and determine the amplitude or relative phase of the reflected or transmitted microwave power at each frequency since this information encodes the state of the sensors. This type of multichannel signal processing is closely related to digital techniques used in modern cellular communication and, consequently, powerful commercial electronics are becoming available to perform exactly this task. Using commercial electronics as a starting point, we will develop software, firmware, and hardware that enable the use of microwave readout techniques in measurement problems relevant to DOE's Office of Nuclear Energy.

The determination of material composition and quantity is fundamental to regulation of the nuclear fuel cycle. These two measurement problems are often intertwined since material quantity is frequently determined by combining separate measurements of total activity and isotopic composition. Gamma-ray spectroscopy using high-purity germanium sensors is presently the state-of-the-art non-destructive technique for determining isotopic composition. However, a variety of systematic error terms limit germanium measurements of isotopic ratios to about 1% accuracy (relative). This error level creates mass uncertainties that greatly exceed the amount of material needed to build a nuclear weapon in the throughput of large facilities such as reprocessing and fuel fabrication plants. Hence, there is a pressing need for improved materials accounting techniques.

Recently, superconducting gamma-ray microcalorimeters have emerged as an alternative tool for non-destructive analysis (NDA) because their spectral resolution is routinely 10x better than germanium and is sufficient to resolve almost all elemental and isotopic overlaps. The best microcalorimeter resolution is 22 eV full-width-at-half-maximum (FWHM) at 97 keV, compared to more than 400 eV for high-purity germanium [Bacrania, 2009]. This improvement in spectral resolution greatly reduces some error terms in key isotopic ratios. However, the deployment of microcalorimeter sensors faces two significant obstacles: first, complexity and associated cost, and second, longer measurement times limited by the number of microcalorimeter pixels that can easily be integrated into a single array. Here, we propose to solve both these problems by developing inexpensive microwave readout techniques that will enable microcalorimeter arrays up to 10^4 times larger than has been shown to date. The same microwave readout techniques will be applicable to a wide variety of other, more conventional sensors that are also relevant for nuclear safeguards.