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Specific NIST Projects in Support of the NIJ Concealed Weapon Detection and Imaging Program

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ABSTRACT

The Electricity Division of the National Institute of Standards and Technology is developing revised performance standards for hand-held (HH) and walk-through (WT) metal weapon detectors, test procedures and systems for these detectors, and a detection/imaging system for finding concealed weapons. The revised standards will replace the existing National Institute of Justice (NIJ) standards for HH and WT devices and will include detection performance specifications as well as system specifications (environmental conditions, mechanical strength and safety, response reproducibility and repeatability, quality assurance, test reporting, etc.). These system requirements were obtained from the Law Enforcement and Corrections Technology Advisory Council, an advisory council for the NIJ. Reproducible and repeatable test procedures and appropriate measurement systems will be developed for evaluating HH and WT detection performance. A guide to the technology and application of non-eddy-current-based detection/imaging methods (such as acoustic, passive millimeter-wave and microwave, active millimeter-wave and terahertz-wave, x-ray, etc.) will be developed. The Electricity Division is also researching the development of a high-frequency/high-speed (300 GHz to 1 THz) pulse-illuminated, stand-off, video-rate, concealed weapon/contraband imaging system.

Keywords: antenna-coupled microbolometer, concealed weapon imaging, Law Enforcement and Corrections Technology Advisory Council, performance specifications, standards, terahertz-wave, video-rate imaging

1. INTRODUCTION

The Electricity Division of the National Institute of Standards and Technology (NIST) through the NIST Office of Law Enforcement Standards (OLES) is involved with four projects to support the law enforcement and corrections (LEC) community. These projects specifically address concealed weapon detection and are intended to:

1. improve the existing National Institute of Justice (NIJ) standards for hand-held[1] (HH) and walk-through[2] (WT) metal weapon detectors (see Sec. 2),
2. develop a guide for the use of advanced concealed contraband detectors (see Sec. 3),
3. develop a prototype "stand-off" system for imaging/detecting weapons concealed on humans (see Sec. 4), and
4. develop, in conjunction with the NIST's Electromagnetic Technology Division, terahertz-wave (100 GHz to 10 THz) detector arrays (see Sec. 5).

The first two projects are in their first year of a two-year plan and the third project is in its second year of a five-year plan. The fourth project started in the 1999 fiscal year. The purpose of this paper is to describe these projects.

The projects addressed by the Electricity Division were among many that were indicated by the NIJ as being high

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priority and that the NIJ intended to support. The NIJ's basis for selection and support are the recommendations from the Law Enforcement and Corrections Technology Advisory Council (LECTAC). The LECTAC consists of high-ranking personnel from local, state, and federal LEC agencies and their purpose is to provide to the NIJ their prioritized requirements and concerns regarding law enforcement and corrections technology. The mission of the OLES is to provide the standards and technology development support required by the NIJ.

To ensure that the results of these projects deliver the maximum benefit to the LEC community, the direction of these projects is guided by LEC input. To obtain this input, several representative LEC agencies were contacted. Because of the large number of LEC agencies and the large variation in size of these agencies, the selected agencies were of medium to large size (number of sworn personnel ≥ 10) that were located near NIST in Gaithersburg, MD or that had representatives on the LECTAC. The selected range of agency size was chosen because it better represents the total number of sworn personnel.[3,4] However, based on discussions with representatives from LEC agencies of all sizes, the requirements expressed by the selected group are consistent throughout the LEC community.

An issue that affects the direction of all these projects is the level of security, which is based on perceived threat. From discussions with many LEC personnel, there appears to be only two applied levels of security; high and low. High security is used in correctional facilities, jails, very-important-person (VIP) security, etc. In high-level security, the LEC community wants to find the smallest possible piece of metal that can be a threat to security, such as a paper clip or the hypodermic needle of a syringe. However, because of limitations of present technology, the LEC community must be satisfied with detecting larger objects, such as handcuff keys, razor blades, etc. The low-level security is more similar to airport security, and in this case the LEC agencies want to find small knives and firearms. The applications for low-level security are courthouses, building security, event security, etc.

2. METAL WEAPON DETECTOR STANDARDS IMPROVEMENT PROJECT

The standards improvement project was implemented because of requests by HH and WT manufacturers and by LECTAC members. The previous standards[1,2] do not address issues presently indicated as being important by the LEC community and do not describe reproducible measurement methods.

A. LEC Requirements for Revised Standard

It was quickly learned after starting this project that the existing NIJ standards were either not known to exist, were not used (if known to exist), or were not useful (if known to exist and had been read). Because the NIJ standards are voluntary compliance standards, it is important that the LEC community becomes aware of the existence of the standards and understands and uses the standards. If this does not happen, manufacturer compliance to the standard may be arbitrary or deficient.

The primary reason the standards were not used or found to be not useful was that these documents did not provide LEC personnel with information they felt to be relevant to their work. The LEC community would like the document to have many uses or contain a variety of information, such as:

1. system or device procurement
2. basic operator training
3. safety (operator and general public)
4. minimum performance specifications
5. easy-to-perform field performance verification
6. performance verification tests (detailed and exacting)
7. theory of operation (brief tutorial)
8. limitations (and reasons)

Some of these topics are contained in the existing NIJ standards but are not presented completely or adequately and, more importantly, not presented in such a way that allow the standard to be easily utilized by LEC personnel.

B. LEC Perceived Detector Inadequacies

The reported inadequacies of the present HH and WT metal weapon detectors are in detection performance and functionally useful features. Both HH and WT detectors have been observed to exhibit inconsistent response to items claimed to have been presented identically in repeated trials. This inconsistent response could be due to interference (electromagnetic), a drift in detector or in emitted power, or object presentation was similar but not identical. These issues will be addressed by requiring compliance to electromagnetic interference (EMI) and quality assurance requirements and by developing reproducible test procedures. It has also been observed that the response repeatability is affected by humidity and temperature changes and by adjacency to moving and stationary metal objects. The environmental issues can also be addressed by requiring compliance to appropriate specifications. However, because the HH and WT devices are metal detectors, the presence of other metal objects will affect detector response. With the WT systems, programming detection sensitivity appears to be difficult and mechanical stability is an issue. With HH devices, durability, low battery power indication, sensitivity adjustment, etc. are problems.

C. Standards Efforts by Other Agencies and Organizations

The American Society for Testing and Materials (ASTM) has several documents pertinent for WT metal weapon detector standards including installation[5], personnel requirements and training suggestions,[6] performance testing,[7] and detection sensitivity mapping.[8] Any relevant parts of the ASTM documents will be referenced and utilized in the revised NIJ standard. The ASTM presently does not have any documents pertinent for HH devices. The performance testing described by the ASTM[7] includes detector sensitivity and various types of interference. The portal mapping described by the ASTM[8] can be accomplished by a system that was built by the Federal Aviation Administration (FAA) of the Department of Transportation (DoT) several years ago or by the smaller system presently being built at NIST. The NIST system is different from the FAA system in that it will provide a map of the magnetic field strength in the three mutually orthogonal directions (call them x,y, and z) of the Cartesian coordinate system, will not require a frame on both sides of the portal, and will be much more compact.

The FAA has performed several tests on HH and WT devices; however, the reports of these tests are restricted (and therefore not referenced herein). The FAA understandably restricts access to certain documents to prevent certain groups and individuals from learning how to defeat the HH and WT devices.

There are several agencies, both state and federal, that have implemented performance tests that were used to develop sole-source procurement procedures. However, these tests are not reproducible. A very comprehensive procurement document, in terms of specification requirements, is a request for quotation from Transport Canada[9] (the Canadian equivalent of the U.S. FAA). Some of the specification topics in the Transport Canada document will be used in the revised NIJ standards.

There are other already-developed standards and guidelines that can be applied to certain performance characteristics of HH and WT devices. These performance characteristics are related to safety, electromagnetic compatibility (EMC), temperature and humidity conditions, and quality assurance. The available standards are from international organizations, federal agencies, and the U.S. military. Wherever possible, these standards and guidelines will be applied in the revised standards. The reasons for using existing standards is to facilitate updating the revised NIJ standards (by referencing the appropriate updated support standard) and to reduce redundant standard development efforts.

D. Design of Test Objects

The Electricity Division has, in cooperation with the Federal Bureau of Prisons (BOP), developed test objects (exemplars) for testing both the HH and WT devices. These exemplars are aimed at addressing the high-security applications of correction facilities, prisons, etc. The exemplars contain machined replicas of the following objects: a 5-cm long (≈ 2") section of hacksaw blade, a razor blade, a #2 Phillips head screw driver bit, a nail clipper (see Fig. 1), a handcuff key, and a 22-caliber long-rifle round. Although some of these items may be similar in shape, size, and material composition, they have all been observed to give different detection responses. Replicas are used instead of the actual items to ensure dimensional and material consistency and to diminish access to dangerous items by the inmates. The replicas are also cast inside a plastic container to further reduce the danger of these items and provide consistent presentation (orientation) of the exemplars to the detector. There are four holes on each of the possible unique orientation surfaces of the exemplars: one hole is a pivot and the others provide for 0°, 45°, and 90° rotations.

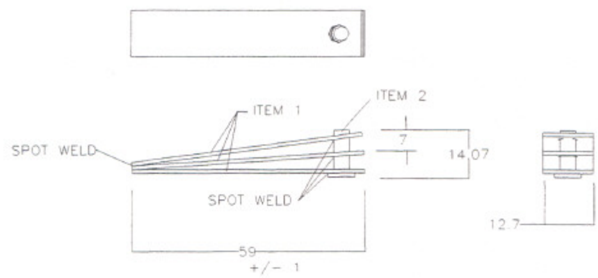

Figure 1. Mechanical drawing for nail clipper assembly. All dimensions are in millimeters.

E. Test Systems

The test systems for both the HH and WT device will consist of an x-y-z computer controlled positioner. Orientation and rotation of the exemplars will be done manually. The magnetic field intensity distribution (in x, y, and z directions) for the HH and WT devices will be measured. For the WT device, detection sensitivity will be inferred from these measurements and using the assumption that the detector antenna loop(s) is (are) symmetric to the emitter loop(s). This mapping will allow the testing laboratory to infer the detection sensitivity as a function of object orientation. The effect of extremes in object speed (or detector speed) on detector response will also be tested. For the WT, the exemplars will be passed through the portal at critical locations and at extremes (maximum and minimum) of object speed. The object speed will be used to assess both throughput capability (detector reset time) and speed of detector response.

F. Required Specifications

The following is a list of specifications the LEC agencies, in general, would like to see in the revised NIJ standard:

electromagnetic compatibility (EMC)
environmental conditions (temperature, humidity, sand, rain, etc.)
mechanical safety (radius of corners and edges, protrusions, etc.)
electrical safety (electrical shock)
exposure safety
mechanical strength (durability, puncture resistance, stability/tip-over, shock resistance)
response time (time to detect/image)
throughput (time between subjects, time between successive images or detection events)
distance to object
object orientation
object speed
object discrimination (for resolving multiple targets)
object material
interchangeability/ common user interface
response repeatability and reproducibility
quality assurance.

3. CONCEALED WEAPON and CONTRABAND IMAGING/DETECTION SYSTEMS USERS' GUIDE

The guide project addresses the requirements of the LECTAC to have information on the use, operation, application etc. of non-conventional weapon detector technology, that is, of concealed weapon imaging/detection systems (CWIDSs). CWIDSs will be used to find objects hidden on individuals that can be used as a weapon or that is defined as contraband. Typically, weapons are thought to be made of metal but, as has been described by the LEC community, weapons can be made of any material. Explosives and biologically and chemically hazardous materials are also weapons. Furthermore, many correction facilities are interested in finding contraband items that are carried on inmates and their visitors. These items may be extra clothing, cigarettes, etc. The CWIDSs addressed here use electromagnetic or acoustic methods to detect a concealed object; chemical sensors will not be considered. Furthermore, the CWIDSs mentioned here will not utilize conventional weapon detector technology. Conventional weapon detector technology has focused on detecting metal weapons and will be defined here as using non-imaging eddy current generation/detection methods; the HH and WT metal weapon detectors typically seen at courthouses and airports are non-imaging eddy current detectors.

A. Guide Requirements

The LEC community would like the guide to provide insight into the different technologies so that they can predict potential problems or benefits in the application of a given technology. In addition, the guide should contain safety information (for the operator and the general public), theory of operation, and limits of operation. Safety is of particular importance because of public acceptance of the CWIDS technology.

The LEC agencies want to know the type of information (image, indicator, alarm, etc.) that is provided by the CWIDS because of potential right-to-privacy issues. That is, if the method is capable of displaying an image, how much detail is shown and how much operator interpretation is required. Detailed images showing anatomical features are not acceptable. Furthermore, viewing articles hidden on an individual may have right-to-privacy ramifications. Although these issues are the purview of the courts, it does affect the design of systems to be developed. If no image is provided, on the other hand, what form does the information take and how is it deciphered by the operator.

Developing detection performance standards for CWIDSs is premature at this time because the standard will be application specific, such as the existing HH and WT standards are application specific. However, if the CWIDS is used to augment a function presently being performed by a conventional HH or WT device, then the HH and WT standard can be applied with the addition of technology-specific safety notes.

B. CWIDS Development Efforts

The development of CWIDSs has been funded primarily by the FAA, the NIJ of the Department of Justice (DoJ), and the Defense Advanced Research Projects Agency (DARPA). These agencies have funded or are funding a variety of different technologies for CWIDS including: active acoustic imaging and detection, passive and active magnetic imaging, passive infrared (or thermal) imaging, active electromagnetic-pulse-based detection, passive millimeter-wave imaging, and active pulsed millimeter-wave/terahertz-wave imaging. The term "active" refers to systems that require illumination of the target by an external non-natural energy source to observe the target, whereas "passive" refers to systems that use existing natural (solar, blackbody, etc.) energy to observed the target.

4. TERAHERTZ-WAVE CONCEALED WEAPON IMAGING

The design of an active imaging system that utilizes a frequency band in the 300 GHz to 1 THz region is being researched for a stand-off concealed weapon imaging system. The term "terahertz-wave" (or t-wave) is typically used to describe that part of the frequency spectrum lying approximately between approximately 100 GHz and 10 THz. The active t-wave CWIDS being considered uses a t-wave source to illuminate the target area and the measured signal is obtained from the power that is reflected from the target (see Fig. 2). Because the CWIDS under investigation is an active system, there are many possibilities for illuminating the target area and subsequent detection of the reflected signal. However, system and performance requirements greatly reduce the number of viable source-detection candidates. Furthermore, NIST does not engage in direct competition with industry and cw systems are presently under development by several companies. The most important performance parameter affecting the viability of an active t-wave CWIDS is the detector signal-to-noise ratio (SNR). The SNR is affected by noise, source parameters, detector parameters, desired gray scale, image capture rate, etc. Possible noise sources are thermal radiation, the detector, the source, and other system electronics. Furthermore, multiple reflections of the emitted (source) power will degrade the SNR. These multi-path reflections can be internal to the source or detector circuitry and in the source-target field. Source parameters that will affect the SNR include antenna beamwidth, frequency bandwidth, continuous or pulsed

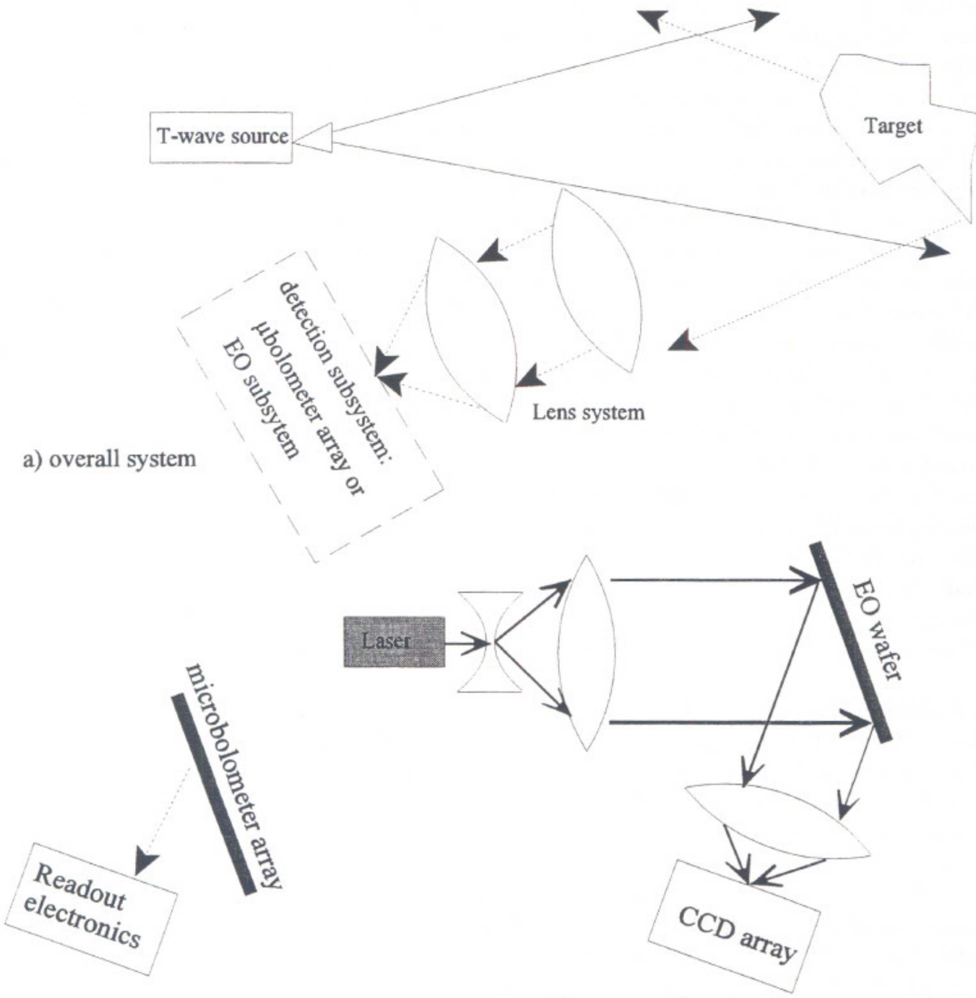

Figure 2. Schematic of possible terahertz-wave concealed weapon imaging/detection subsystems showing the two detection subsystem considered: a) a microbolometer array and b) an electrooptic-based sensor/transducer.

operating mode, modulation mode for a continuous-wave (cw) source, etc; detection circuit parameters that can affect SNR include local oscillator power (if applicable), demodulation method for a modulated continuous source, noise-equivalent power, filter bandwidths, operating temperature, amplifier gains, detector responsivities, antenna efficiencies, etc. Many types of systems can be designed to be CWIDSs, ranging from a system using a high-voltage pulse-biased optoelectronic pulse generator with an amplified short-pulse laser system for electrooptic sampling to a system using a spatially-scanned cw millimeter-wave diode with a single beam-lead diode detector. However, neither of these systems would be acceptable at this time: the cost, weight, and size of the first system are too large and the image acquisition time too slow for the second system. Therefore, other factors exist which affect the viability of a candidate CWIDS and these factors are cost, weight, size, required operating expertise, utility (power, cooling) requirements, ruggedness, etc. These parameters exclude many possible system designs because of limitations of existing technology. For example, far-infrared gas lasers and vacuum tube devices (such as, backward-wave oscillators) are not considered as possible sources because of their size, weight, fragility, cost, etc. Of course, as technology improves, so does the viability of different system designs.

Our focus for the t-wave CWIDS has been on solid-state sources and detectors. Over twenty different modulation and associated detection methods have been examined analytically and experimentally (using a radio-frequency system).

Approximately twenty to thirty variables (depending on the modulation method) were used in the analytical assessment of the candidate methods. The result of these studies is that a pulsed source with synchronously gated detection would provide the highest SNR, be the easiest to implement, and have potential for the lowest cost. Also, commercial entities are pursuing various cw methods. It is important to distinguish between a pulsed source and a pulse-modulated cw source. A pulse-modulated cw source is a cw source with an output that is modulated by a switching (gating) device: the average output power is simply the product of the un-modulated average power and the switching (gating) duty factor (which is less than 1). The pulse power for a pulse-modulated cw source is equal to the cw power. Therefore, in the best case, there is no SNR improvement for a pulsed modulated source without the use of additional circuitry, such as lock-in amplifiers. On the other hand, a pulse source can generate watts of peak power with only micro watts of average power. A CWIDS using a pulsed source with gated detection may achieve significant SNR improvements because the observed noise power decreases with decreasing gate width while the pulse power is constant (for the gate width being greater than or equal to the pulse width). To achieve the improvement in SNR using pulse methods, it is necessary that the detector be gated to acquire information only during the duration of the pulse and that the detector gating be synchronized with the emitter. Therefore, the general system architecture for the t-wave CWIDS will be a synchronously gated pulse detection system. Although the general architecture of the CWIDS has been defined, there are many parameters for the source (transmitter) and detector (receiver) that must be determined. For the transmitter element, these parameters include type of source (pulsed narrowband, pulse broadband, pulsed noise), operating frequency band, repetition rate, pulse duration, pulse power, beam profile, beam divergence, antenna efficiency, type of illumination (flood, scanned area, scanned line, scanned point), etc. For the receiver element, important parameters include gate duration, gate synchronization jitter, antenna efficiency, detector responsivity, response time, format (rectangular array, linear array, single device, scanning), noise equivalent power, operating temperature, etc. Many of these parameters will be limited by the availability of components.

The transmitter section will utilize a single pulsed diode noise source capable of providing 10 ns wide pulses with a duty factor of 10^{-4} and 1 W peak power. Initial system development will use a source with a nominal center frequency of 96 GHz because of the availability of components at this frequency. The noise will have a bandwidth of approximately $\pm$ 3 GHz based on the present availability of pulsed noise sources. A noise source will be used instead of a cw source to reduce the deleterious effects of coherent radiation in imaging: the broader the spectrum of the noise source the better the image. The advantage of broadband noise for imaging is best described by considering photographic images where objects are illuminated by a broadband noise source such as the sun or a flash bulb. For a t-wave CWIDS, however, the noise bandwidth is limited, by available sources, to about $\pm$ 3%. This is analogous to using either the yellow-red (centered at 600 nm) or blue-green (centered at 500 nm) part of the visible spectrum (400 nm to 750 nm) for obtaining a photographic image. The output of the noise diode will be launched using a scalar horn (approximately $\pm$ 7° beamwidth) that is designed to illuminate a 1-m radius object area approximately 8 m from the source. The scalar horn, compared to other antennae, provides uniform exposure of the target area.

The receiver section of the imaging system will include appropriate imaging optics, such as a zoom lens, the detector elements (either a microbolometer array or a large-area electrooptic sensor), synchronization and drive electronics, and the interface between the detectors and common video imaging electronics. The detector array will be a monolithic structure (described in the next section) with fixed detector (pixel) spacing. To adjust the spatial resolution of the system, a zoom lens system will be developed. Initial design of the receiver system will not utilize delay (phase) information and, therefore, the system will not be able to provide distance data. However, the image will be analogous to video images where distance information is via viewer/operator interpretation. Distance information could be obtained by using accurate (sub-ns) and low-jitter (sub-ns) timing circuitry. Distance information is necessary for systems requiring automatic (without operator intervention) action.

Image acquisition will be performed by one of two methods being explored at the Electricity Division. One method is based on microbolometer arrays (see Sec. 5) and the other on the linear electrooptic (eo) effect.[10] The eo-based detection system will require the use of eo materials, appropriate optics, and a pulsed light source. The eo material will be used to convert the reflected t-wave signal to an optical signal.[11] The optical signal may then be detected by a conventional low-cost CCD camera.[12]

5. TERAHERTZ-WAVE DETECTOR ARRAYS

Work has been started at NIST to develop room-temperature, antenna-coupled microbolometer detector arrays. The primary advantage of these devices over conventional hybrid methods is the much reduced size and that array fabrication will use conventional silicon integrated circuit (IC) equipment and technology. Furthermore, the wavelength (frequency) sensitivity/range is defined by the antenna geometry and not material properties. Antenna-coupled microbolometers (single element) have been developed to detect radiation down to 10 µm wavelengths.[13] The primary emphasis of this work will be to develop thermal isolation structures and an array design that is compatible with existing IC processing technology, microbolometer materials, and video capture electronics. Niobium (Nb) will initially be used for the microbolometer material because its fabrication process is well developed and room-temperature electrical behavior well understood. However, other material systems, such as vanadium dioxide, may be examined.

This work, if successful, will allow the development of multi-spectral imaging arrays on the same wafer area. For example, the typical diameter for a planar antenna is between one wavelength (λ) and 3 λ. By interleaving sub-arrays of antenna-coupled microbolometers, where each sub-array is sensitive to a different part of the electromagnetic spectrum, a single-chip multi-spectral array can be fabricated. Consider a 1 λ diameter, 100-GHz detector sub-array located on a square grid. There exists sufficient space between the detector antennae to fit antenna-coupled microbolometers operating at, for example, 500 GHz (600 µm), 1 THz (300 µm), and 30 THz (10 µm).

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