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ABSTRACT

Subwavelength imaging has recently seen increased interest in multiple fields. There are various applications and distinct contexts for performing subwavelength imaging. The technological ways to proceed as well as the benefits obtained are as various as the applications foreseen. To benefit from subwavelength imaging a way around standard imaging procedure is often required.

INO is also involved in this activity mainly for the infrared and the THz wavebands. In the infrared band a detector with 17 um pixel pitch, larger than the pixel, was used in conjunction with a microscanning device to oversample the image at a pitch much smaller than the wavelength. In this case the pixel size is in the order of the wavelength but the sampling is at subwavelength level. In the THz band a 35 um pixel pitch is used at wavelength ranging from 70 um to 1,063 mm to perform imaging through various objects. In this case, the pixel itself is smaller than the wavelength.

Subwavelength imaging is not without its challenges, though. For instance, while the use of ultra-fast optics provides better definition, their design becomes more challenging as the models used are at their very limits. Questions about information content of images can be raised as well. New research avenues are being investigated to help address the challenges of subwavelength imaging with the goal of achieving higher imaging system performance. This paper discussES aspects to be considered, review some results obtained and identify some of the key issues to be further addressed

INTRODUCTION

Subwavelength imaging has recently seen an increase in interest in multiple fields [1-5]. There are various applications and distinct contexts for performing subwavelength imaging. The methods for producing subwavelength images and the corresponding benefits are as varied as the applications. To benefit from subwavelength imaging, significant modifications to standard imaging procedures are often required.

INO is involved in this activity mainly for infrared and THz waveband imaging [6-8]. In the LWIR infrared band, a detector with a 17 µm pixel pitch was used in conjunction with a microscanning device to oversample the image at a pitch much smaller than the wavelength. In this case, the pixel size is on the order of the wavelength but the sampling is at subwavelength level. In the THz band, a 35 um pixel pitch microbolometer array is used to detect wavelengths ranging from 70 um to 1.063 mm, in order to perform imaging through various objects. In this case, the pixel itself is smaller than the wavelength.

Subwavelength imaging is not without its challenges. For instance, while the use of ultra-fast optics provides better spatial resolution, their design becomes more challenging as the models used are at their very limits of optical capabilities. Questions about the information content of images can be raised as well. New research avenues are being investigated to help address the challenges of subwavelength imaging with the goal of achieving higher

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imaging system performance. This paper will discuss aspects to be considered, review some results obtained and identify some of the key issues to be further addressed.

INFRARED IMAGING

Surveillance applications using infrared imaging typically require both long distance imaging and wide angle coverage. While those two modes are essential to perform adequate surveillance, they are at the same time contradictory in terms of optical requirements. For a detector array with a given pixel pitch, the longer the focal length, the better the capability to recognize a given target. However, a longer focal length also means a narrower field of view. To limit the number of cameras to be deployed for a given application, for example border surveillance, a compromise must be made between field-of-view and recognition distance. Another factor to consider when designing an optical system is the size of the system to build. A detector array with smaller pixels allows for optics with a smaller diameter and focal length hence a smaller and more compact system. Ideally, it can be concluded that to have a compact high performance system, the number of pixels in the detector array has to be as large as possible and the size of the pixels as small as possible. Obviously there are limitations in the pixel size of commercially available detector arrays. Moreover, when a detector array becomes larger its surface increases resulting in less detectors per wafer and lower production yields due to higher probabilities of having defects. This in turn will substantially influence the manufacturability and the price of the detector arrays.

A way to circumvent the difficulty of producing large, high resolution detector arrays is to combine a detector array of high but reasonable resolution with a microscan mechanism. The microscan mechanism slightly moves the image by a fraction of a pixel along one dimension, then by a fraction of pixel in the orthogonal dimension, then by a fraction of pixel in the opposite direction to the first displacement. Finally, the image will return to its original position. If each displacement distance corresponds to half a pixel, 4 steps will be required to move the image and return to its original position. The final image is generated by interlacing all 4 images together according to the microscanning displacement sequence. The result is an image with twice the spatial resolution. Since 4 images are required to create a single high resolution image, the effective frame rate for acquiring 2x higher resolution images is four times less than the nominal frame rate of the camera. Nevertheless, the gain in information is worthwhile, particularly for long distance surveillance. In its more general definition, microscanning introduces a fractional displacement of the pixel pitch. The resulting final reconstructed image is composed of a number of images equivalent to the number of displacements required to cover the whole pixel. For instance, if the microscan displaces the image by half a pixel, 4 images are used to generate a full frame and hence the size of the image will double in each orthogonal direction of the detector array. Similarly, if the displacement of the microscan is $1/8^{th}$ of a pixel, 8 steps are required along each dimension of the detector and a total of 64 images will generate a final image of 8192 x 6144 pixels for a detector resolution of 1024 x 768 pixels. Since current high resolution microbolometer detectors have a pixel pitch of 17 um which is close to the diffraction limit for wavelengths between 8 to 12 µm, one could ask if such an increase in resolution is worthwhile. In 2015, Caufield [5] et. al. demonstrated the benefits of very small pixels on focal plane arrays. The rationale behind their conclusion is that oversampling of a scene is of benefit since it provides a clear reduction of the aliasing. Moreover, the authors pointed out that the detector noise is not taken into account when considering only the MTF of the PSF for an optical system. Oversampling provides a mean to reduce the noise and hence improves the resolution.

It was demonstrated [6] that at least up to a microscan factor of 2 x 2 pixels, there is a clear gain in resolvable image details. To test the image detail resolving limits achievable by microscanning, microscanned images of up to 16 x 16 steps were acquired using INOs HRXCAM-16K camera, illustrated in Figure 1. In this camera, microscanning is achieved using catadioptric optics. Compared to standard refractive optics, catadioptric systems usually show higher transmission at higher spatial frequencies. This is quite interesting since in 1981 Oppenheim [9] showed that most of the information in an image is contained in the phase. The phase information is obtained when the amplitude of a Fourier transform is set to unity. The author links the unitary Fourier transform to an over weighing of the high spatial frequency components of the image and hence most of the information is in fact represented in the high frequency content of the images. This explains at least qualitatively the usefulness of microscanning catadioptric optics which tend to transmit the high spatial frequencies which contain the largest amount of image information. Microscanning provides increased sampling of an image and spectrally separates (in terms if spatial frequencies) the various orders resulting from the digitization of the image. In short, higher spatial frequencies are transmitted through the optical system, these higher frequencies which contain most of the information are then sampled at higher frequencies which in turn reduces the aliasing and improves image resolution.

Figure 1: HRXCAM-16K an infrared camera with a catadioptric optics that can oversample the images with a microscan of 16 x 16 pixels yielding images of 16348 x 12288

An example of an image as well as it zoomed version, illustrating the benefits of microscanning, is provided in Figure 2. The image of the Vancouver skyline shown below was obtained in 8x8 microscan mode (8192 x 6144 pixels). The following images show the area enclosed in the square rectangle zoomed in, to illustrate the real image resolution enhancements provided by microscan.

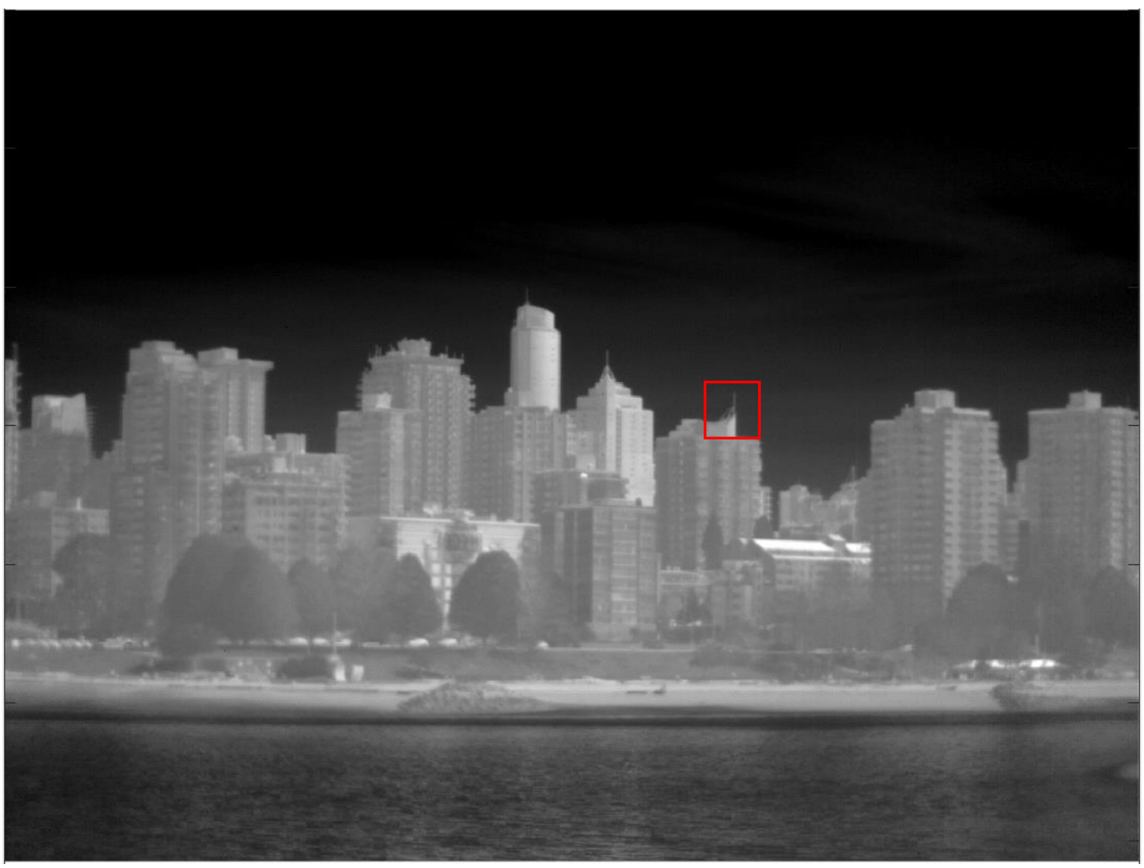

Figure 2: Image of Vancouver captured with the HRXCAM-16K with a microscan operating at 8 x 8 steps.

Figure 3 shows a zoomed-in section of Figure 2 shown by the square. The image to the left was obtained in 8x8 microscan mode, while the one to right is from the non-microscanned (1024x768) image. It can clearly be seen that some fine details in the bars on the tower, are identifiable on the microscanned image but not on the non-microscanned image.

Figure 3: Zoomed-in image microscanned, 8x8 steps, (left) and original (right) of the Vancouver image.

In this case the original pixel size of 17 µm is larger than the wavelength. Microscanning at 16 steps brings the sampling step size down to 1.0625 µm. This kind of imaging therefore requires a very precise adjustment of the microscan systems. Indeed, it has been found that going to 16x16 microsteps requires a much more precise alignment and calibration than in the 2x2 microsteps. Slight misalignments of the microscan mechanism at levels far inferior to the wavebands used, 8 to 12 um, can induce significant artifacts in the 16 x 16 image if not carefully compensated for.

TERAHERTZ IMAGING

INO has developed a compact imager with 384 x288 pixels for imaging in the terahertz and millimeter wavebands [7, 8]. This imager is illustrated in Figure 4.

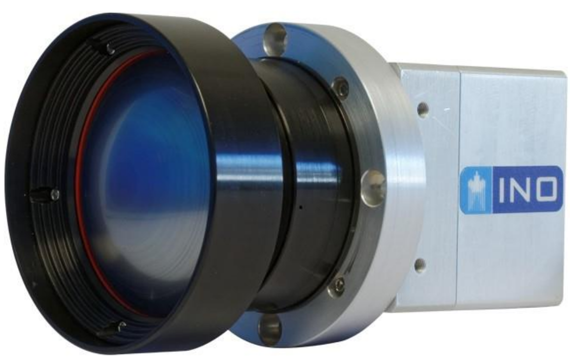

Figure 4: Terahertz video-rate imager of 384x288 pixels.

The sensor exhibits very good sensitivity over a very wideband from 40 um up to 3.0mm. The pixel pitch of the detector is of 35 µm which is clearly smaller than the wavelength. The detector was used in various imaging systems for wavelengths much larger than the pixel pitch. Nevertheless, some very good images were obtained even at wavelengths much larger than the pixel pitch. Figure 5 shows preliminary tests performed with an illumination source having a wavelength of 118 µm. The same scene was measured with a 160x120 pixel imager having a 52 um pixel pitch and with a 384 x288 pixel imager having a 35 um pixel pitch imager. It can clearly been seen that, despite a pixel pitch much smaller than the wavelength, the image using 35 µm pixels is better defined. The reduction of aliasing as can be observed by the reduction of staircases in the diagonal features is a consequence of the higher spatial sampling frequency.

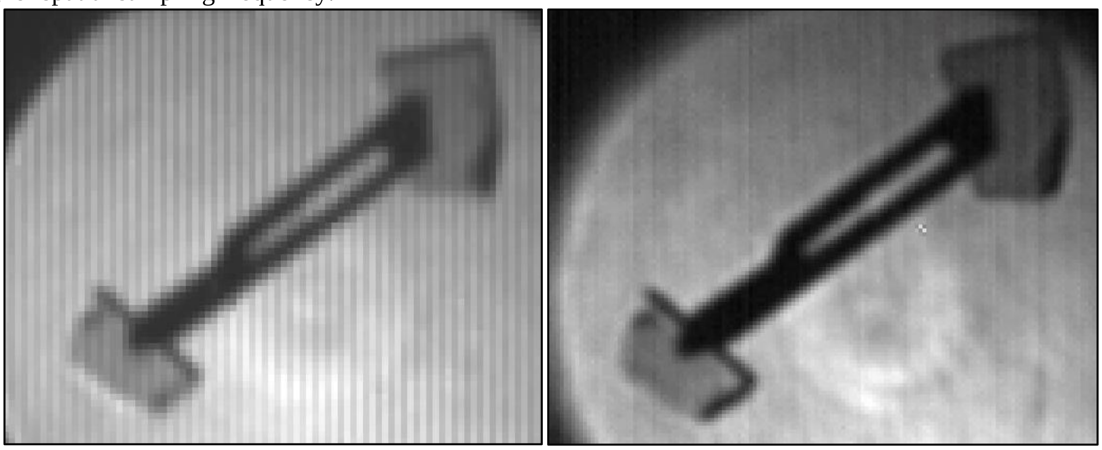

Figure 5: Terahertz images of the same scene captured with a 160x120 pixel imager with 52 um pixel pitch pixel.

To further improve the native resolution in the terahertz waveband, INO has developed very fast optics. In the infrared waveband, typical optics exhibit f-numbers around 1.0 and the best infrared optics show f-numbers of 0.866. For the THz band, faster optics help in getting the best possible spatial resolution when using long wavelength illumination sources, by decreasing the point spread function and increasing the light collection. This is especially useful for field applications where the emission power of currently available terahertz and millimeter sources is still limited. For this reason, THz optics with f-numbers down to 0.7 have been designed and fabricated. The optics can be used over a very wide spectral range.

The challenges related to the development of terahertz components are diverse and significant. Since the f-number needed to improve the light collection and the resolution are very low, the collection angles that have to be addressed are significantly larger than the ones covered by the paraxial optics approximation. Also, material properties in the terahertz waveband are usually not as well characterized as in the infrared waveband. Consequently, this poses real challenges to the optical designer when it comes the time to predict the performances of a system. As an additional challenge, since most THz band illumination sources are based on diodes, they are coherent in the terahertz and millimeter wavebands. The illumination setup must therefore be specifically designed in order provide uniform illumination and to account for the potential presence of interference fringes.

Furthermore, some optical components with features comparable in size to the wavelength may behave totally differently in the terahertz. For instance, a metallic slit will suddenly begin to act as a polarizer if its physical size approaches the wavelength dimension. The optical properties of a component are thereby changed simply due to the change of the source wavelength. When designing an imaging system, each component has to be analyzed carefully by considering the waveband used in order to fully understand its behavior when used in subwavelength imaging mode.

INO`s approach has been to apply these optical design considerations to the terahertz and millimeter wavebands. In doing so, a two dimensional array camera with specifically designed superfast optics has allowed to obtain images using illumination wavelengths slightly larger than 1 mm, with. work underway to reach wavelengths up to 3 mm. So far, our design approach has produced excellent images at wavelengths that were not considered usable even a few years ago. The Figure 6 shows a transmission image of a wooden object taken at 580 um. A further illustration is given in Figure 7, where a composite image of an opaque ESD bracelet is obtained at 750 µm. The image shows the capability to see through the opaque object and obtain information on its hidden content such as wires.

Figure 6: Terahertz image in transmission of a wooden object captured at a wavelength 580 um.

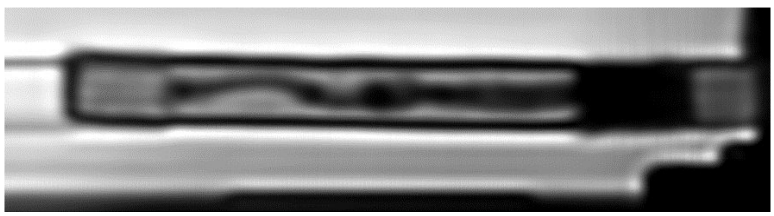

Figure 7: A composite terahertz image, captured at a wavelength of 750 um, of an opaque ESD bracelet using a 384x288 imager with 35 um pixel pitch.

CONCLUSION

Subwavelength imaging is a research topic for various groups around the world. INO`s optical design approaches to improve resolution, light collection and illumination have yielded excellent image quality using pixels smaller than the illumination wavelength. This is explainable, in part by the use of superfast optics to reduce the point spread function, and by the inherent oversampling achievable by microscanning to reduce aliasing and noise. Future work will involve the use of image processing techniques to try to extract further information that is captured but not yet apparent in the unprocessed images.

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