Techniques and Developments in THz Standoff Imaging

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Introduction

The part of the electromagnetic spectrum, that lies between the microwave region and the infrared region is called the THz range. The community does not fully agree on the limits of this range yet, but we can say it roughly starts between 0.1 THz and 0.3 THz and ends between 3 THz and 10 THz. A standoff imaging system detects the radiation from a distance of several meters. To avoid losses on the path through the air between the object and the imaging system, frequencies which are significantly absorbed by air (up to a few dB/m) should be avoided [1]. There are many gaps of high transmission in the spectrum, hence enough frequency-ranges are left to choose from.

The further selection of an operating frequency depends on several fundamental and technological aspects. The spectroscopically interesting range is above one THz, where most features of substances like explosives or drugs can be found [1]. The higher frequencies also provide higher resolutions with given apertures. On the other hand the penetration of materials like fabrics is better with lower frequencies. Furthermore, electronic sources and detectors are easier to be realized at lower frequencies and hence more powerful and cost-effective (they may not be available above 2 THz at all, up to now). We will come back to frequency aspects in more detail later in this survey on THz standoff imaging. But at first, we should continue with some fundamental classification.

Passive and Active Imaging Techniques

In THz-imaging, we differentiate between passive and active techniques. The passive ones either use the radiation emitted by the object itself, or use radiation that was emitted by natural sources like the sky and then reflected by the object. Active systems use THz-sources for illuminating the object. This has consequences in different fields. The ethical concerns for passive systems are lower, because people are not exposed to additional radiation, so there are no reasonable concerns in respect to possible health risks. In the case only the radiation emitted by the person itself is used for creating the image, even the privacy is enhanced, because the body is evenly bright and one rather sees the silhouette of the person than the shape of the body. Additionally, the resolution is rather limited and concealed objects are visible as shadows, because they block the radiation emitted by the bright body. With external illumination whether natural or artificial, things change significantly. Because THz wavelengths are orders of magnitude longer than visible ones, most surfaces are glossy in this regime. The detected power strongly depends on the angles of the reflecting surface, the detection optics and the illumination. This pronounces the shape of the object that can easily be interpreted by our visual processing system. It is also an issue for active standoff imaging systems in the security range, because depending on object-, detection- and illumination angles, some areas of an image may not provide a detectable signal and allow for a concealed object staying in the dark [2].

While passive imaging systems are fundamentally limited to the radiation available, active systems can/have to provide the radiation that is required for specific applications. Narrow-band illumination together with heterodyne helps to achieve efficient noise suppression and high dynamic range imaging. For detection of specific substances, one can adapt the illumination spectrum to the features of the substances of interest. The controlled variation of the illumination wavelength allows for techniques like frequency modulated continuous wave (fmcw) operation which additionally provides distance information on the detected reflections. This 3D-information can be very helpful for recognizing concealed objects.

Aperture Size

The diffraction limited lateral resolution for a circular aperture can be estimated by using the Rayleigh-criterion: $r=\frac{1.22\,\lambda d}{D}$, where r is the distance between two object points, which can still be separated, $\lambda=\frac{c}{v}$ is the wavelength, while c is the speed of light and v the frequency of the radiation, d is the distance between the aperture and the object and D the diameter of the aperture. For standoff-imaging the value of d is several meters. With wavelengths in the sub-mm range and targeted resolutions in the mm-range, aperture diameters D in the order of one meter are a typical result. These can be realized in the conventional way (usually as big metallic mirrors), with synthetic apertures (only in the active case; as known from the radar field) or both approaches can be mixed.

The real aperture size is also relevant for the signal power that can be received from the object. The solid angle covered by the aperture is approximately $\Omega=\left(\frac{D}{4\mathrm{d}}\right)^2$. If radiation emitted by the object itself is to be detected, this value is important in respect to power available for detection. If an external illumination is being used, one has to differentiate between scattering characteristics of the object. If the power is rather evenly distributed over a wide solid angle (scattering), the detectable power is approximately proportional to the area of the aperture, like in the case of the emitting object. If the object is reflecting rather specularly (i.e. like a mirror), the solid angle of the aperture determines the range of surface orientations, from which reflections can be detected [3]. For random surface orientations, this means the probability of detecting a signal from that surface.

Detector Requirements

The available power is a significant limit on all THz standoff imaging systems. In the case of passive systems, the limits are rather fundamental ones like the properties of black body radiation. In the case of active systems, the power limits are set by the costs and dimensions of available sources today, but might be limited by regulations on the admitted THz-exposure of the human body in the future. With limits for available power as well as for the time which is required to acquire an image, sensitive detectors are indispensable. Again, several options are available. One can use two-dimensional detector-arrays and image the object plane onto this array, one can use a one-dimensional detector array together with a one-axis scanner or a single detector together with a two-axes scanner. The lower the number of detectors is, the higher get the performance requirements of the detector for maintaining the image quality (number of pixels, dynamic range) with given illumination power. Two-dimensional scanning might not be an option for high (i.e. video-) frame rates at all.

For a power detecting (incoherent) imaging system, the noise equivalent power (NEP) for 1 Hz bandwidth should not exceed $\frac{P_I \cdot M}{N \cdot \sqrt{f} \cdot SNR}$, where P_I denotes the input power available per pixel, M the number of detectors, N the number of pixels per frame, f the rate of the frames and SNR the targeted signal to noise ratio for the pixels. To determine the detectable power from an object (black body), one can approximate the integration of Plancks Law by $P_D = \eta \cdot A \cdot \Delta v \cdot \frac{2\pi h v^3}{c^2 \cdot (\exp((h \cdot v)/(k \cdot T)) - 1)}$, where η is the ratio of the power available for the detector to the total power emitted from the area, A is the area from which the power is emitted (for example the pixel size in the object plane), Δv is the detector bandwidth, v the center frequency, T the temperature. With the equations given above, one can estimate the requirements for the detector NEP of an stand off imaging system, which detects the thermal object radiation.

To estimate the performance of an optimum system for imaging the thermal emission of a object (black body), we would assume a perfect efficiency $\eta = 1$ (no photon is lost), a resolution of one wavelength $A = c^2 / v^2$ and a bandwidth of approximately one octave $\Delta v = v$. The number of photons n, which can be detected in t=1 s is given by $n = P \cdot t / (h \cdot v)$ and the shot-noise limit for the SNR is given by $1/\sqrt{n}$. If these values are combined with the formula given above and the assumption that the object is at about room-temperature, one can calculate the optimum SNR for an integration time of 1s with only the frequency v as a parameter: $SNR = \sqrt{\frac{v \cdot (\exp((h \cdot v)/(k \cdot T)) - 1)}{2\pi \cdot t}}$. It can be seen that not only the resolution is better at higher frequencies, but also the number of photons is higher. Thermography systems usually operate at wavelength of a few microns, that means above 10 THz.

Examples of projects realted to stand off imaging systems

In the project THz-Videocam [4], superconducting detectors with a NEP in the order of $10^{-16} W / \sqrt{(Hz)}$ are used and a frame rate of 1 Hz is currently reached. One of the targets is to reach video-rates by utilizing a higher number of detectors.

In the project Lynkeus, two different approaches have been realized. The first one [2,3] is a fully electronic system based on a coherent source/detector pair. The source has an output power of 1 mW, while the single heterodyne detector can detect amplitudes equivalent to $10^{-13} W$ with an integration time of $100 \mu s$. In combination with a two-dimensional scanner the typical acquisition time for one frame is 9s. The second one [5] converts the THz-field imaged onto an electro-optical crystal to a modulation of infrared light. This modulation is analyzed by a photo mixing device (PMD)-camera, that was designed for time of flight applications. In this way one can realize a multi-pixel detector even for the upper THz-range. Although THz-imaging could be demonstrated with this approach, the performance required for standoff-imaging applications is not reached, yet.

The project TeraCam also deals with two different approaches, both of them aim at active standoff-imaging at 812 GHz. The first [6] utilizes detector arrays based on micro-bolometers without cooling, but with an antenna for each pixel. The second one [3] utilizes 32 heterodyne receivers sharing one local oscillator and a one-dimensional rotational scanner. The target is to get close to video-rates (at least 10 fps, one per revolution of the mirror).

The project TEKZAS combines a THz-optical-parametric-oscillator as a source with a detection based on conversion with a electro-optical crystal ([7], an approach similar to the one in the Lynkeus project). The imaging frequency is 1.5 THz, additionally spots of interest found in the image can be examined with THz-spectroscopy in order to identify suspicious substances.

Three Dimensional Imaging

If the phase of the THz-wave which is received by a coherent imaging system is measured (like with the heterodyne systems in Lynkeus and TeraCam), it already contains information on the object distance with a high resolution, but only with the small ambiguity range of half a wavelength, which is too small for most standoff imaging applications. A technique, that can provide a depth resolution, which is better adapted to the lateral one, is called fmcw and was transferred from the radar field to THz-frequencies. The frequency of the radiation emitted by the source is modulated with linear ramps (in the simplest case). One part of the power is directly fed into the detector, while the other is sent to the object, where it is reflected or scattered and some of it returns through the quasi-optics also to the detector. It took a longer way and is hence delayed by a certain time in respect to the signal directly fed into the detector. Because the frequency of the signal changes linearly with the time, its has different frequency and the difference is proportional to the delay time (and hence the distance of the object point) and the slope of the frequency change. The difference frequency is directly available as beat signal at the detector and is measure of distance. In practice, the frequency can't be increased forever and hence a sawtooth-shaped modulation is used. The frequency-measurement is limited to a single ramp and its accuracy is limited by the duration t_r of this ramp . The depth resolution and the range of uniqueness are given by these equations: $\Delta r = \frac{c}{2\,\Delta v}$ and $r_{uni} = \frac{c}{2t_r}$. In THz-imaging, resolutions in the order of millimeters and ranges of uniqueness in the order of meters are typical. A demonstration of the fmcw-technique in THz-standoff imaging is given in [8].

Conclusions

Standoff-imaging in the THz-regime is an emerging field. This range in the electromagnetic spectrum has several properties, which make it interesting for applications. Today, the target applications for most standoff systems are in the security field. Here, mainly the low photon-energy of THz-radiation (below the ionizing threshold) and its penetration ability through most of fabrics are the primary benefits. An important difference between the technologies is the kind of illumination used. From the ethical point of view, systems using the radiation emitted by the object itself are the best solution. The object is not exposed to additional radiation and its three-dimensional shape is barely visible. A technological benefit is that the radiation can be detected from any surface orientation. The fundamental performance limit of these systems is given by the laws of black body radiation, which allow for higher performance with increasing frequencies. Big real apertures and detectors at cryogenic temperatures are mandatory to reach high performance. Active systems on the other hand can be more versatile, because they allow for employing approaches like fmcw or synthetic aperture operation. While fmcw provides additional depth information, that is very helpful for identifying concealed objects, synthetic apertures can be very helpful to limit the size of a practical imaging system. These active systems are usually based on fully electronic sources and detectors, which become more costly with increasing frequencies. Electro-optical detection allows for coherent operation with rather frequency-independent costs in the THz-range, which makes them an interesting approach especially for higher frequencies. For all THz-standoff imaging techniques a high detector performance is required. Active systems additionally need powerful sources. Nowadays systems performance is usually limited by the costs of these components but not the technical feasibility. We surely can expect some advance in THz standoff imaging in the future.

References

1. Liu HB., Zhong H., Karpowicz N., et al.: “Terahertz spectroscopy and imaging for defense and security applications”, PROCEEDINGS OF THE IEEE, Vol. 95(8), pp. 1514-1527 (2007)
2. von Spiegel W., am Weg C., Hils B., et al.: “Active THz imaging system with improved frame rate”, SPIE Defense, Security, and Sensing Proceedings Vol. 7311, pp. 73110O (2009)
3. von Spiegel W., am Weg C., Henneberger R., et al.: “Illumination aspects in active terahertz imaging”, IEEE Transactions on Microwave Theory and Techniques, THz Technology: Bridging the Microwave-to-Photonics Gap (to be published)
4. May T., Zieger G., Anders S., et al.: “Passive stand-off Terahertz imaging with 1 Hertz frame rate” - art. no. 69490C, Proceedings of the SPIE, Vol. 6949, (2008)
5. Friederich F., Schuricht G., Deninger A., et al.: “Phase-locking of the beat signal of two distributed-feedback diode lasers to oscillators working in the MHz to THz range”, OPTICS EXPRESS, Vol. 18(8), pp. 8621-8629 (2010)
6. Dillner U., Kessler E., Baier V., et al.: “A 64-pixel linear thermopile array designed for vacuum environment”, Proceedings of IRS² 2006, in: Sensor + Test 2006 Proceedings, AMA Service GmbH, Wunstorf, 2006, pp. 295-300 (2006)
7. Meng FZ., Thomson MD., Blank V., et al.:”Characterizing large-area electro-optic crystals toward two-dimensional real-time terahertz imaging” , APPLIED OPTICS, Vol. 48 (27), pp. 5197-5204 (2009)
8. Cooper KB., Dengler RJ., Llombart N., et al.:”Penetrating 3-D Imaging at 4- and 25-m RangeUsing a Submillimeter-Wave Radar”, IEEE Transactions on Microwave Theory and Techniques, Vol. 56(12), pp. 2771-2778 (2008)