Terahertz Technology

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The unique features of terahertz radiation in the context of industrial applications are highlighted. The most common terahertz systems and the way they have been applied in the industry are described. The main barriers from wide spread industry adoption and the outlook of terahertz technology are also discussed.

terahertz | industrial application | thickness measurement | defects localization | material characterization | THz Camera | Non-Contact Testing | Non-Destructive Testing | Time-Domain Spectroscopy | Continuous Wave

Introduction

Terahertz (THz) refers to electromagnetic radiation of frequencies around 10^12 Hz. The general definition covers the frequency range between 0.1 THz to 10 THz [1], which correspond to wavelengths between 3 mm to 0.03 mm, respectively. As the bandwidth lies between microwaves, which are generated electronically, and the infrared, generated photonically, producing and detecting THz radiation had been difficult due to a lack of suitable materials and methods, although the potential utility of this band was suggested as early as 1970 [2]. However, since the successful implementation of ultrafast lasers [2] research in the field took off in the 1990s and has been growing ever since. Today a wide range of THz systems and applications have been developed across a broad range of sectors, including biological [3], medical [4], and industry [5][6].

One of the most distinctive features of THz radiation is its ability to penetrate a wide variety of non-conductive materials. In this respect, it is similar to microwaves but the spatial resolution is much higher given the shorter wavelength [7]. In the industrial context, this allows examination and detection of defects in small devices such as integrated circuits [8], as well as structural defects such as cracks in concrete [9].

Another distinct feature of THz radiation is its strong sensitivity to water and other polar liquids [3],[10]. This sensitivity stems from the fact that hydrogen bonds between water molecules resonate strongly at THz frequencies, absorbing most of the incident THz radiation in the process of dipole re-orientation. This allows for the precise measurement of moisture content and the monitoring of water ingress in a wide range of building materials and products [11].

As to the safety of THz radiation, it is non-ionizing due to its low photon energy (~4.1 meV at 1 THz [12]); this allows THz systems to be deployed in the field without the complication of stringent safety requirements as that of, for example, X-rays [[13]].

Applications in Industry

The ability of THz to penetrate most non-metallic materials allows non-contact examination of materials that are opaque in the visible range such as concrete, insulating foam, and paint. The properties of interest across the industries may be broadly categorized into three areas—layer thickness, defects and contamination, and material characterization.

Although the key parameters of interest are application-specific, the advantage of terahertz over other mature technologies in non-destructive testing (NDT) is in providing new information. For example, in determining paint layer thickness in the car manufacturing industry, existing ultrasound techniques require physical contact between the sensing head via a gel medium; this restricts the use of ultrasound on dry paint. Terahertz, on the other hand, can be used without any physical contact, providing information on fresh paint layers and the drying process [[14]].

Across applications, the bandwidth and the signal-to-noise (SNR) ratio are perhaps the most common parameters used for comparing different terahertz systems, but specific requirements are application dependent.

Thickness measurements have been demonstrated with both TDS and CW systems. In a TDS setup, reflections from the layer interfaces are identified as peaks in the time domain. The thickness can be determined by the time delay as

$$2d = \Delta t(c/n), \quad (1)$$

where d is the layer thickness, Δt is the time between the reflections, and n is the refractive index of the material. For sub-micron layers where the reflection peaks overlap, several numerical techniques have been demonstrated [[15],[16]].

Thickness measurements with CW offer a compact and cost-effective alternative to TDS. For phase extraction, coherent detection can be achieved via a homodyne detection scheme. As demonstrated in [[17]], a photomixer involving two distributed feedback (DFB) lasers achieved a resolution of 1 GHz. The same group also demonstrated a non-frequency sweep method via Gouy phase shift interferometry for fast data acquisition [[18]].

Fibre-coupled systems eliminate the need for bulky free-space optics and mechanical movements, yielding compact and robust NDT tools. An ultrafast, fully fibre-coupled CW THz spectrometer was demonstrated in [[19]]; spectra over a bandwidth of 2 THz can be acquired at a speed of 24 Hz.

The main challenge in detecting structural defects lies in generating sufficient contrast of the defects (e.g., a subsurface void) against the background. For example, cracks and voids in concrete are more apparent in a THz image when filled by water or contaminant other than air. This is due to higher absorption by the ingress material reflecting less radiation compared to that of the surrounding concrete. In the case of porous materials such as foam, the difference between defective voids and internal air pockets can be difficult to distinguish, particularly if the air pockets are of a submillimeter size or larger also scatter the THz beam.

Much work on material characterization with THz has aimed to establish a database, of which other applications can make use. One example is in production quality control, where a sample’s electrical properties such as conductivity must be investigated to meet specific criteria before proceeding to the next stage of production.

Outlook

The utility of terahertz radiation in NDT has been demonstrated, as noted in the preceding sections. However, several obstacles prevent wide industry adoption.

Firstly, the relatively expensive equipment deters businesses, which are commonly driven by immediate financial benefits. While various prototypes demonstrated good precision or resolution. Trading precision for cost is a strategy that more and more manufacturers are pursuing. Also, being able to utilize existing manufacturing equipment and processes is expected to lower the barrier for manufacturing. An example of this is the FET-based THz camera.

Secondly, the speed of measurement is critical in an industrial setting that may be less obvious in a research environment. The labour cost involved is magnified by the usage of the system. The net financial benefit of each measurement would need to be positive and large enough for the timely recoupment of the investment.

Finally, the portability and the robustness of the system typically falls short given the environments in which systems will be potentially used. The equipment would be frequently exposed to mechanical and acoustic vibration, heat, humidity, and the weather. Measurements may need to be done in hard-to-get-to places with limited space. Being portable and robust encourages its use, while lowering the training requirement for the operational and maintenance personnel.

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