Market Opportunities for Rydberg Based GHz to THz Sensors

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1 EXECUTIVE SUMMARY

Terahertz radiation presents a myriad of opportunities for sensing and imaging. Many envisaged THz applications arise from the fact that specific rotations, vibrations or librations of molecules and molecular aggregates occur in this frequency range. THz radiation can: pass through many materials that are opaque in the visible region (e.g. clothing, plastics and paper), allow the spectroscopic distinction of liquids and solids such as explosives, drugs and biomolecules, monitor spatial distributions of chemicals and pharmaceutical active ingredients, and identify defects by strong scattering conditions. Furthermore, THz radiation is non-ionizing and safe in comparison to x-rays. These sensing and imaging attributes enables a large variety of applications for the hyperspectral detection and identification of molecules in diverse areas. Examples of the main application areas of THz imaging currently include:

- Stand-off detection of hidden objects and weapons
- Non-invasive medical and dental diagnostics
- Detection of cracks and defects in materials
- Non-destructive rapid fault isolation in integrated circuit packages
- Drug discovery and formulation analysis of coatings and cores
- Non-contact imaging for conservation of paintings, manuscripts and artefacts
- Monitoring of crop and plant hydration levels

The terahertz region of the electromagnetic spectrum sits between the well exploited optical and radio wavelengths; beyond the long-wave infrared, yet shorter than the sub-millimetre wave band. The technology in this spectral region (Generally defined as being between 0.3-10 THz) is significantly less well advanced than for the optical and radio bands, leading to what has become known as the ‘terahertz gap’. Despite research and development in this area of high potential since the 1960’s, the source and detector technology required for effective implementation has remained frustratingly complex, expensive, impractical, and ultimately lacking the necessary performance.

Rydberg methods presented here offer an opportunity to harness this spectral region in a simple method that offers direct spectrally resolved THz imaging and field measurements traceable to SI units.

2 RYDBERG QUANTUM TECHNOLOGY

2.1 Introduction

The reproducibility, accuracy and stability of quantum objects, such as atoms, have made many of the standards and measurement techniques established early in the past century relics. Most progress in adopting atoms for standards has been made in measuring atomic transition frequencies that are now used for length and time standards. Quantum-system-based sensing approaches have generally demonstrated 2 orders of magnitude better accuracy measurements enabling them to replace classical approaches across the majority of systems.

A remaining bastion of metrology yet to be upgraded to quantum level accuracy has been the measurement of electromagnetic fields. Recent work using Rydberg states of Alkali atoms is allowing the accurate measurement of electromagnetic fields from those with radio frequencies, through microwaves to terahertz radiation. The high level accuracy offered by quantum technologies is applicable to a range of existing markets and in the longer term will open up a range of applications and develop new markets with new capabilities. This document aims to gauge this potential.

2.2 Rydberg Quantum Technology Approaches

Unlike traditional approaches that focus on the classical picture of electromagnetic waves, Rydberg quantum technologies (RQT) makes use of the quantum nature of atoms to absorb and emit at well-defined, discrete frequencies. The practical benefit of this is that RQT does not suffer from the technical challenges of producing ever-smaller structures to accommodate higher frequency electromagnetic waves. In addition, E-field measurements performed with RQT (using quantum-based electromagnetically induced transparency (EIT) techniques) yield measurements that are traceable directly to known atomic properties, making them in effect, self-calibrating. Through these methods Rydberg-type techniques have been exploited to read out radio frequency fields, to demonstrate precision microwave electrometry and for sub-wavelength imaging of microwave fields.

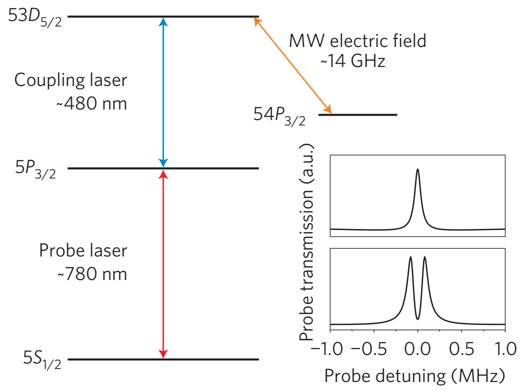

Figure 1: Energy level diagram. The energy level diagram for an example four-level system to detect microwave. The top part of the inset shows an example EIT feature associated with the three-level system without a microwave electric field. The bottom part of the inset shows an example of the bright resonance that is produced within the EIT window when a microwave electric field is present. Ref: *Nature Physics* **8**, 819–824 (2012).

Rydberg atoms are atoms in highly excited states with large principal quantum numbers, n, and long lifetimes. These closely spaced high n energy levels allow the possibility for transitions for low-energy electromagnetic radiation such as radio frequency

(RF), microwave and THz to take place and become detectable by a variety of schemes centred around exploiting Autler-Townes splitting. To reach and detect these transitions a number of methods are possible. The principal method has been through the use of EIT.

Rydberg Quantum Technology, wherein lasers are used to create Rydberg atoms sensitive to electromagnetic frequencies in the conventional RF, microwave, millimetre wave, and sub-terahertz frequency ranges, is a technology currently under development. In this technique, alkali atoms placed in a vapour cell (a glass cell with atomic vapour inside) are excited optically to Rydberg states and the applied electromagneric field alters the resonant state of the atoms. This approach exploits the sensitivity of the high-lying Rydberg states to electromagnetic radiation.

EIT is a quantum interference process in which two excitation pathways of a three-level system interfere to produce transmission on an atomic resonance. A superposition 'dark state' is formed from the ground and Rydberg states, and as both of these states have long decay lifetimes, the spectral width of this dark state is extremely narrow. As EIT depends on quantum interference, it is exquisitely sensitive to phase disturbances, transitions out of the participating states and energy level shifts of the three-level system. The addition of a electric field that is resonant with a nearby Rydberg transition, a fourth level, shown on the right of Fig. 1, breaks the symmetry of the EIT interference and can produce a spectrally sharp bright resonance within the EIT line shape. The detection of the line-shape change allows the measurement of the resonant (RF, microwave or THz) radiation. The high accuracy of this approach is due to the EIT technique making an amplitude measurement (the desired quantity) from a frequency measurement (a measurement that can be performed very accurately) (Ref: *Nature Physics* 8, 819–824 (2012).

2.3 Rydberg Fluorescence Imaging

Following on from EIT, Wade et al. demonstrated direct coupling of the investigated radiation, in this case THz, to a fluorescent state (Ref: *Nature Photonics* 11, 40–43 (2017)). This was achieved by multiphoton excitation to a fluorescent Rydberg state with the THz photons allowing for a direct mapping of the THz to optical regimes. This approach is a significant advancement on the detection of EIT, despite being based on similar physical principles. Both schemes still demonstrate a marked advancement in capabilities for the detection and quantification of EM radiation.

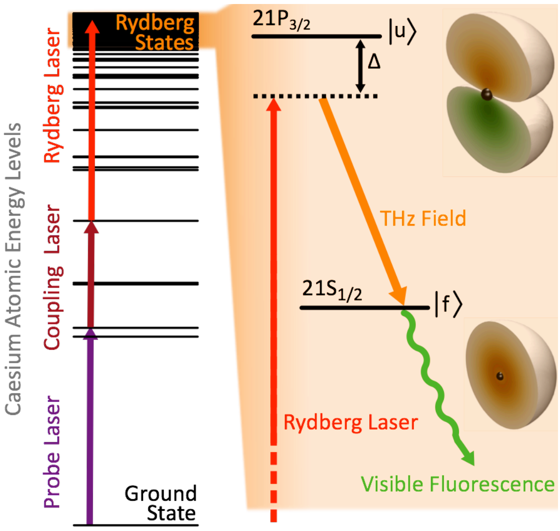

Figure 2: Caesium atomic energy levels and laser excitation scheme: Three infra-red lasers combine with the THz field to excite atoms to the final Rydberg state. The THz-induced visible fluorescence emitted by the Rydberg atoms indicates the spatial profile of the THz field. Ref: *Nature Photonics* 11, 40–43 (2017)

In this scheme, the 'Rydberg atoms' are used to 'map' longer-wavelength photons (LW-EM) onto shorter wavelength optical photons. The alkali metal atoms are excited to a Rydberg state by a multi-photon process involving both optical photons from laser sources and a LW-EM photon as shown in Figure 2. The excited Rydberg atom then rapidly decays, emitting an optical photon in the process as fluorescence. As the creation of the Rydberg state by this method requires the presence of LW-EM photons, a correctly pumped alkali metal vapour will only fluoresce in the presence of a LW-EM field. Therefore the longer wavelength electromagnetic radiation attenuated from passing through media under investigation will be directly translated into fluorescence intensity. The result is a fluorescence 'image' of the resultant LW-EM field. The process has a THz to fluorescence ratio of 1:1 and is highly sensitive. Furthermore, the transition is highly wavelength sensitive, allowing for spectrally resolved images to be obtained. Capturing the fluorescence and imaging the pattern of the fluorescence with a camera allows real-time observation of the electromagnetic fields with sub- wavelength resolution.

While both technologies make use of quantum-optic induced spectroscopic effects,there is an inherent advantage of the fluorescence method over the EIT method. The fluorescence captured in the latter method is an unambiguous signal distinct in wavelength from all likely sources of background noise. This is somewhat tempered by the fact that the fluorescing atoms emit in the full solid angle, of which only a small fraction can be collected, and an initial calibration to relate the fluorescence intensity to absolute field intensity needs to be performed to use this method for electrometery, but may still find use in applications where background noise is an issue.

2.4 Technical Implications of Rydberg Fluorescence Imaging

A number of factors make Rydberg fluorescence imaging useful for adapting to a sensor-based technology:

Resolution of the detected LW-EM Frequency - as the excitation of atoms by photons is an undeniably quantum process, only LW-EM photons of a particular wavelength will be detected. It is easily possible, however, to tune the frequency of electromagnetic radiation that the system is sensitive to. As the Raman excitation that creates the Rydberg atom is a multi photon process, it is possible to adjust the frequency of one of the optical photons to detect photons of slightly different frequencies. This could be considered the 'fine frequency tune'. As the Rabi-frequency of such a transition is inversely proportional to the detuning from an upper atomic state, there is a limit to the extent in which the 'fine tune' is viable. This limitation can be overcome by switching to a different Rydberg state for LW-EM detection once the two-photon detuning becomes too large. This 'coarse frequency scan' is feasible as Rydberg states are much more closely spaced than lower-level atomic states (due to the loosely bound electron). A third approach is also possible, the application of a static electric field will provide a frequency shift to the Rydberg states, hence shifting the detected THz frequency. The exact manner of the shift will depend on the particular Rydberg state of interest. Between three of the most commonly used alkali metal vapours in quantum optics (Rubidium, Potassium, and Caesium), viable Rydberg states span the region 0.3 to 3 THz and can be extended to detect radio frequencies and microwaves. An alternate scheme would be the construction of a miniaturised thin-walled glass cell, fibre coupled to allow for pumping. The cell could then be placed near the sample under test and the fluorescence in the cell imaged with a camera or other sensor. The latter scheme sacrifices some potential utility for increased robustness. It has been suggested (Ref: *Nature Photonics* 11, 40–43 (2017)) that to perform experiments observing near-field effects, samples be placed in a low-pressure alkali metal vapour atmosphere. The practicalities of this arrangement should be carefully considered. Alkali metals are notoriously reactive, and this should be borne in mind when choosing appropriate samples for testing. Potential solutions to some of the issues around this method of testing are discussed further in this document.

Resolution of the intensity of the LW-EM field - It is also possible to measure the intensity of the THz field with this scheme in a manner that does not require inferring EM field from fluorescence brightness. By monitoring the transmission of the lasers through the atomic vapour as the frequency of one of the lasers is scanned across the Rydberg feature, one will observe a quantum-optical spectral feature termed 'Autler-Townes Splitting'. This effect is well known in the quantum optics field. By measuring this splitting, one can directly measure the LW-EM field strength.

2.5 Advantages of Rydberg Fluorescence Imaging

Near Field Regime:

Acquisition speed - Other methods of measuring LW-EM fields on a sub-wavelength scale usually involve mechanically scanning a LW-EM sensitive element across the field. This leads to long acquisition times for many measurements, ranging from days (Scanning Near-Field THz Microscopy) to the order of hours (THz Digital Holographic Imaging). As no mechanical scanning of elements is required for this Rydberg-based technique, the practical limiting factor is likely to be the acquisition time of the camera (of order 10's ms).

Transparency - The multi-photon process is a stimulated Raman transition to a Rydberg state. Due to this, the number of LW-EM photons entering and exiting the vapour cell should be the same. This would allow a detector based on this technology to be placed in a THz beam without fear of destroying the beam. This is in contrast to other techniques.

Far-Field Regime:

Acquisition speed - The majority of existing LW-EM detection technologies (Golay cells, Bolometers, etc.) operate using thermal processes. The Rydberg method instead operates on much more rapid optical processes. This is reflected in the response/rise times of the different technologies.

Inherently frequency sensitive - Unlike thermal sensors, the Rydberg detection scheme has 'built in' frequency sensitivity. Thermal-based technologies require additional elements to perform wavelength discrimination- usually a Fabry-Perot cavity.

2.6 Applications of Rydberg Fluorescence Imaging

1) Near-field Immersion Sensor

The goal of this application is to detect LW-EM Fields on a sub-wavelength scale. The THz regime would give the highest resolution achievable, however the same method is capable in the microwave regime. A sample will be exposed to LW-EM radiation, and the impact of the sample on the LW-EM wave will be observed. As near-field sensing requires that the field close to the sample be observed, the most obvious placement of the sample is inside an alkali metal atmosphere. This rules out a sealed vapour cell in this application. One possible alternative would involve a resealable glass cell attached to alkali metal dispensers and a roughing pump. During the exchange of samples the cell would be flooded with an inert dry gas such as argon, then pumped down and sealed. The dispensers would then be activated, re-filling the sample chamber with the required alkali vapour. When this process is complete, the LW-EM and counter propagating light sheets would be applied to the cell/sample. The fluorescence from the Rydberg decay would then be captured by a camera, which in a single image shows the structure of the LW-EM waveform before and after the sample in the cell.

2) Electric Field Sensor / Spectrum Analyser / Power Meter

The goal of this application is to measure the power spectral density of a LW-EM beam. In this case, a small alkali cell can be used, as no spatial information needs to be gathered. Such an arrangement lends itself to miniaturisation. The cell is optically pumped, and LW-EM is directed towards it. Either a photomultiplier tube or a photodiode (depending on sensitivity requirements) is used to collect the fluorescence from the Rydberg atoms. A computer control system scans the LW-EM sensitivity by sweeping the frequency of the required lasers. This will give information about the spectrum of the LW-EM radiation. Using this information, the computer control system then performs the power measurement on detected frequencies.

3) Hyperspectral Imager

The goal of this application is to measure the spatial distribution of the LW-EM radiation in a spectrally sensitive manner. In this case, an alkali metal cell of large area cross-section is used. The cell is optically pumped and then can be treated as a LW-EM sensitive photographic 'plate'. Images of the fluorescence are captured with a camera. This LW-EM sensitive plate can potentially be used in applications similar to luggage scanners or medical imaging. The advantage over microbolometer arrays lies in that the plate is only sensitive to one LW-EM frequency specified by the user, so this plate could be used as a LW-EM hyperspectral imager. The powers required to pump such a plate optically are extremely large and could be problematic. This could be circumvented by using a combination of rapidly spinning or reciprocating optics, and curved reflectors to rapidly raster smaller beams across the plate, or the traversing of a light sheet.

2.7 Technical Risks

We outline some potential technical risks with these approaches:

Condensation of alkali metals on vapour cell walls - under certain temperature conditions, Alkali metal vapour can adsorb to the walls of gas cells, forming a mirror-like coating that would inhibit the performance of the detector. This can be solved with a straightforward temperature monitoring/heating system that ensures that the cell walls are maintained at the correct temperature.

Imaging requiring high intensity laser excitation - To perform the excitation of Rydberg atoms by the stimulated Raman transfer process, a comparatively high intensity beam may be required. Average Intensities of 10 MWm^{-2} have been used in demonstrations (Wade 2016). This is not an issue provided the volume of pumped gas desired is small, however, if an application requiring a pumped gas of large cross sectional area is desired, this intensity requirement has the potential to become prohibitive. As an example, to pump a 10 cm x 10 cm cross-section gas cell, a beam of 10 kW power would be required to maintain average intensity. This problem can be circumvented in two ways, firstly by scanning a smaller beam of more modest power across a larger pump area, or by reducing the multiphoton detuning of the scheme, which would relax the power requirements at the expense of increasing background noise (due to increased non-LW-EM dependent Rydberg atom creation).

2.8 System Costs

The Rydberg techniques have a generalised set of similar components that are listed below. It should be noted that these estimates are first iteration prototype cost estimates and that system costs would be reduced as higher TRLs are reached.

Table 1: Component descriptions of items common to all Rydberg Quantum Technology approaches

Component	Quantity	Cost	Total
Locking systems	1	£5,000	£5,000
Acousto-optic modulator(s)	2	£600-700	£1,200-£1,400
Semiconductor lasers	2	£4,000	£8,000
Titanium sapphire laser	1	£100,000	£100,000
Alkali cell(s), enclosed cell	1	£300-£400	£300-£400
Sensor- camera/PD/PMT	1	£1,000 - £500	£1,000 - £500
Total			£115,000-£115,800

Component Descriptions:

Two semiconductor laser systems - will provide the initial stages of excitation to Rydberg states. The power requirements for these stages are modest, average intensities of order 10 KWm^{-2} will likely be sufficient. These lasers will be stabilised to a frequency reference (an alkali metal vapour cell will probably be the most appropriate solution), and hence some tunability will be required. External cavity diode lasers (ECDLs) or distributed Bragg reflector (DBR) lasers would be the most economical option here, and are well-understood technologies.

A *titanium sapphire laser* - will provide the final optical excitation stage to the Rydberg state. This stage has significantly larger power requirements than the other stages. Additionally, this laser will need to have flexible tuning properties to access the different Rydberg states to maximise electromagnetic spectrum sensitivity.

Acousto-optic modulator(s) - will likely be required for frequency shifting lasers on the MHz level. The number and nature of the modulators will depend on the exact locking /detuning scheme

A glass Alkali vapour cell - transparent to all RF, microwave, THz and optical frequencies concerned will be needed. Will probably contain a mixed vapour of Cs, Rb and K. Dimensions, volume and nature of the cell will depend on specific application. A near field immersion sensor is a particularly special case.

Semiconductor lasers for initial stages of Rydberg Excitation – Likely either distributed feedback (DFB) lasers, ECDLs or similar lasers would suit- power requirements are modest, but would need some tunability in order to lock (with some offset) to atomic transitions.

3 TERAHERTZ REGIME

3.1 THz Sensor Competitor Analysis

Table 2 shows the main types of THz detectors currently commercially available and their comparison with a generic Rydberg system. A colour code system has been used in which red indicates 'bad', green 'good' and yellow as 'average' in comparison. In general the proposed Rydberg system has all comparable capabilities as competitor systems with none missing. Notably, the system does not require any chopping, can provide absolute power measurements and is able to measure near-field unlike its competitors. The system is the leader in response time at μs to sub μs time scales. The Rydberg system matches bolometers as being able to display images and not having a max THz power. Being able to display an image almost instantaneously without the long wait times for a bolometer of ms, makes the Rydberg system highly advantageous. It is likely the Rydberg system will have a high weight in early prototype phases, however as the higher technology readiness levels (TRLs) are reached this will be expected to reduce to less than for bolometers which are inherently bulky and heavy due to a reliance on cryogenic cooling. The Rydberg system does not

Table 2: Comparison table of the main classes of THz detector

Technology	Bolometer	Golay	Pyroelectric	Rydberg
Requires chopping?	100's Hz	20 Hz	5-10 Hz	No
Cost	High	£10k	Low	£27k
Known suppliers	Irlabs	Tydex, Microtech	Centec	None
Response time (s)	of order ms	25 ms	μs-ms	μs to sub μs
Noise equivalent power (W/sqrtHz)	$1*10^{-10}$	$1*10^{-10}$	$4*10^{-10}$	Unknown
Weight (kg)	10's	1's	0.2	Unknown
Frequency range (THz)	0.15-20	0.1-50	0.1-30	0.01-3
Max THz power (μW)	None found	10's	100's	None found
Spectral info & filterless?	No	No	No	Yes
Absolute power measurement?	No	Yes	Yes	Yes
Imaging?	Microarrays possible	No	No	Yes
Near Field?	No	No	No	Yes
Cooling?	Cryo-genic	no	no	no

lead on spectral range, however, this should be more than sufficient for analyte spectral identification.

3.2 Overview of THz Applications

Terahertz radiation presents a myriad of opportunities for sensing and imaging. Many envisaged THz applications arise from the fact that specific rotations, vibrations or librations of molecules and molecular aggregates occur in this frequency range. A comprehensive overview of terahertz applications is shown in Figure 3, which identifies four main application areas: industrial non-destructive testing, defence and security, biomedical and miscellaneous other. Sub-segments of

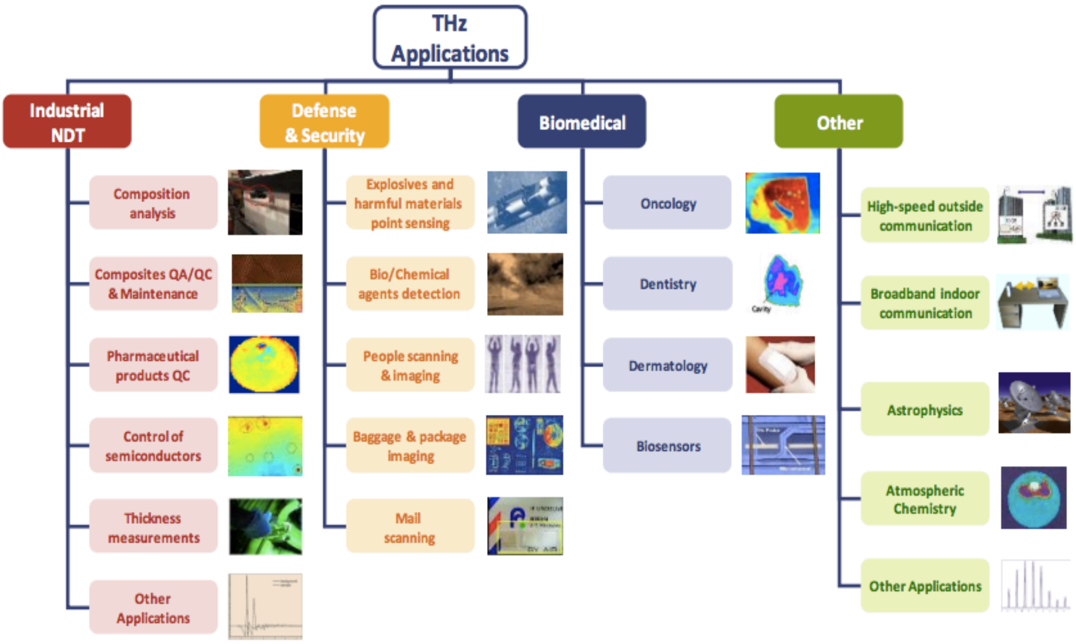

Figure 3: Primary application segments and sub-segments of terahertz technologies (Tematys, 2013).

these four areas are defined, and a number of highly attractive areas for the exploitation of this technology can be identified. In addition, there are also several areas that the technology is somewhat less suited to. The examples below illustrate that there are a plethora of potential applications for THz instruments in a general sense, particularly if such systems exhibit a wide spectral coverage to maximize application flexibility.

3.3 Overview of Terahertz Spectroscopy Market

According to a market report by Marketsandmarkets (Ref: Terahertz Technology Market, April 2016, SE 4268, marketsandmarkets.com) the global terahertz technology market is expected to reach $ 489.8 Million by 2022, growing at a compound annual growth rate (CAGR) of 31.83 % between 2016 and 2022. This growth can be attributed to the anticipated high adoption rate of terahertz technology-based products for laboratory research applications, and growing demand for these products from the defence & homeland security and medical sectors.

Terahertz imaging systems are expected to lead the global terahertz technology market. The market for terahertz imaging systems held the major share of the overall terahertz technology market (by type) in 2015. However, the market for terahertz communication systems is expected to grow with the highest CAGR between 2016 and 2022. THz band communication can help mitigate the spectrum scarcity and capacity limitations of current wireless systems, and enable new applications both in classical networking domains as well as in novel nanoscale communication paradigms. This is expected to drive the market for terahertz communication systems. The Asia Pacific region is expected to experience the highest CAGR between 2016 and 2022, which can be attributed to the increase in initiatives, such as heavy investments in R&D, to encourage the adoption of terahertz technology, taken by the countries such as China, India, and Japan in this region.

The market for laboratory research applications is expected to be the segment with the highest CAGR between 2016 and 2022. The terahertz technology market is not mature, is characterised by highly fragmented commercial operations and is still experiencing continuous technological advancements. Hence, the technologies used to manufacture the terahertz technology-based products are still the focus of extensive R&D activities. The market is dominated by the key players such as Advantest Corporation (Japan), TeraView (U.K.), Menlo Systems GmbH (Germany), Acal plc (U.K.), and Microtech Instrument Inc. (U.S.).

The global terahertz technology market is segmented on the basis of type, technology, application, and region. The main types of terahertz technology-based systems include terahertz imaging systems, terahertz spectroscopy systems, and terahertz communication systems. The main applications of terahertz technology-based systems are terahertz imaging, spectroscopy, and terahertz communication system applications. In addition, the market is also segmented on the basis of technology into terahertz sources and detectors.

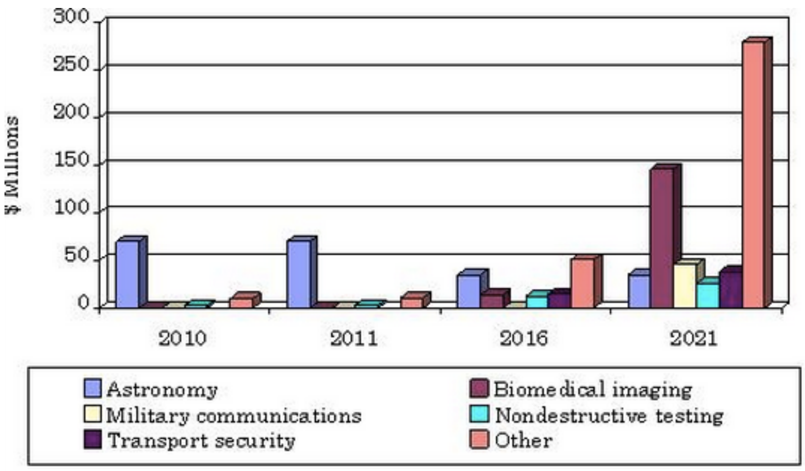

Figure 4: A breakdown of the terahertz market by top-level application area (McWilliams, 2012)

According to market estimates by McWilliams in 2012, shown in figure 4, astronomy research is currently the largest single application of THz systems. However, by 2019, THz transport security and computing applications are expected to surpass astronomy in importance. By 2024, astronomy applications should drop to fifth place, behind computing, transport security, biomedical imaging and military communications. THz imaging devices are the largest device segment throughout the period under review. By 2023, the market for computer-related THz devices, primarily high-performance computer interconnects, should be nearly as large as the market for imaging devices, 32% of the total market vs. and 34%, respectively. Meanwhile other THz sensors such as THz biochips and moisture detectors should account for nearly 18% of the market, and communications-related devices 12%.

3.4 THz Imaging for Industrial Non-Destructive Testing

Non-destructive testing (NDT) is in itself an important and growing industry involving R&D, sensor and instrumentation supply chains, alongside a service-provision sector. When deployed to best effect as part of the complete engineering design process, it delivers safe, reliable and long lasting structures such as power stations, aircraft etc. Every day more than 25,000 inspections are carried out in factories and on-site in the UK to detect defects and damage in a huge range of products, plant and structures; it is estimated that there are more than 120,000 inspectors operating worldwide (Ref: A Landscape for the Future of NDT in the UK Economy, March 2014, www.materialsktn.net).

Table 3: The key sectors where NDT is focused are high growth both globally and in the UK. Transport and aerospace are export intensive sectors. Realising this growth cannot occur without NDT as an enabler. Ref: A Landscape for the Future of NDT in the UK Economy, March 2014, www.materialsktn.net

Sector	NDT linkage	UK Growth %/annum
Energy	High	2.5
Nuclear	High	4.0
Aerospace	High	4.8
Automotive	Medium	3.2
Renewable	Medium	12.5

NDT delivers high impact in terms of safety and asset management for client industries such as aerospace, power generation and transport. NDT is crucial for the development of new manufacturing methods and engineering materials, for assuring the integrity of much of the UK infrastructure and for asset life management. NDT levers a much greater benefit to end users through intelligent management. Regulatory bodies demand that NDT is used to demonstrate compliance with safety and other legislation, and for unregulated industries the commercial advantages of reduced warranty claims, improved plant reliability and higher customer satisfaction justify its use.

This is clearly a highly promising market sector for THz imaging and is already partly established and is projected to grow to ~$30m per annum by 2021 (Figure 4). It can be characterised as a broad field with highly fragmented specific application requirements. The relatively flexible THz technology is well positioned to meet the technological challenges associated with penetrating this sector. In particular the ability to have a reduced form factor gas cell located on the end of an optical fibre can allow for the detector to access confined locations, which competitor systems would find difficult.

Activities in material inspection and quality control have recently gained significant momentum as THz waves can enable defect detection under strong scattering conditions. THz radiation is widely used to measure the thickness of materials and detect the distribution of matter and its structure. The ability to spectrally analyse material further emphasises the roles possible. Unlike ultrasound, terahertz imaging can detect cracks hidden in multi-layered structures. THz light allows imaging through coatings and structures within plastics, ceramics and other polymeric and fiber composites. It can successfully identify defects and abnormalities from foreign material inclusions, debonding and delamination, mechanical impact damage, heat damage, and water or hydraulic fluid ingression.

Examples of industrial applications that will be made possible by the Rydberg THz detector include:

- Condition monitoring of lubricating oils in engines and other machinery, in situ and in real-time, using an installed module; to detect oil degradation, contamination, oxidation or burn products, and metal particles.
- Condition monitoring of fuel in tanks, e.g. in shipping, in situ and in real-time, using an installed module; to detect contamination, sediment, solid residues, and metal particles.
- Inspection of coating uniformity, of paints or other non-metallic coatings, either in-line during manufacturing or post-production; for quality control of layer thickness, adhesion, and air bubbles.
- Non-destructive inspection for metal corrosion concealed by over-coated paint; using either a hand-held scanner or an automated scanner rig.
- Monitoring of moisture levels during drying e.g. in paper manufacturing, in-line and in real time; to achieve optimal uniform drying and minimise drying costs and fuel consumption.
- Structure analysis of ceramics and composites. Investigate flaws, defects and buried structures in advanced composites and ceramic materials. Terahertz radiation is ideal for analysis of advanced composites and ceramic materials and is capable of providing insight into the structure of optically and infra-red opaque ceramic materials. This is useful for aircraft ceramics and composites, imaging of coating structures on refractory ceramics and investigation of vehicle ceramic catalysts for defects and carbon deposits

3.5 Non-Destructive Testing Market

According to a report by Marketsandmarkets (Ref: Non-Destructive Testing (NDT) Market, January 2017, AS 2320, marketsandmarkets.com), the non-destructive testing (NDT) market is estimated to be $15.06 Billion in 2016 and is projected to reach $24.23 Billion by 2022, at a CAGR of 8.24% from 2016 to 2022. 2015 is considered as the base year and the forecast period for this report is from 2016 to 2022. Non-destructive testing techniques are increasingly utilized by varied industries such as aerospace, oil & gas, petroleum, and construction, among others. Innovations in the non-destructive testing market have increased commercially after the introduction of advanced equipment. Advancements in the field of non-destructive testing have further offered huge growth potential for new technologies, of which THz imaging would be one.

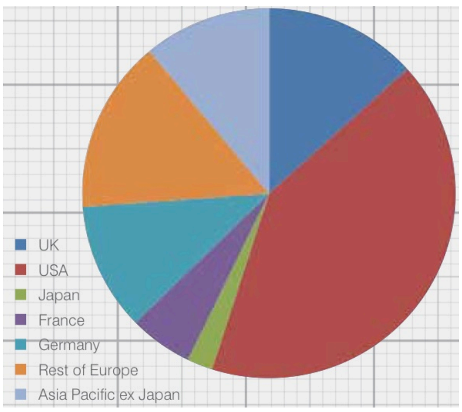

Figure 5: Global distribution of 180 key NDT supply companies. Ref: A Landscape for the Future of NDT in the UK Economy, March 2014, www.materialsktn.net

The extent of the current UK market is not yet well quantified but the UK's national body, The British Institute of Non-Destructive Testing (BINDT) has 172 company members covering the equipment supply, training, service and end user sectors. This constitutes the majority of the commercial organisations involved in NDT in the UK. The manufacturing sector employs large teams of trained NDT inspectors as most parts are inspected multiple times through the manufacturing and service cycle. Plant operators (Eg. O&G, power generation and transport) employ NDT specialist to manage and perform inspection, and often procure NDT services from the supply chain.

The UK has traditionally been strong in NDT technology and innovation, but in common with many other nations, the sector is split into a few transnational groups (Eg. Inspection Technology, Doosan, Olympus NDT, Oceaneering, Intertek etc). There are still robust niche players offering unique capabilities, and in fact, the UK punches above its weight, supplying, according to a survey by global industry analysts, 24 key companies, from an international pool of 183. Barriers exist, in that when a new inspection technology is developed by academic R&D or by the supply chain (often by SMEs), it will not be adopted widely by end-users without first being validated and without adequate standards back up. Validation is very costly and in the current environment standards take many years to generate.

3.6 THz Imaging for Defence and Security

The potential for point sensing of harmful materials such as explosives, chemical agents and biological hazards is of primary interest, and which the Rydberg THz detectors are undoubtedly well-suited to address. Work has also been undertaken to investigate the possibility of remotely detecting chemical and biological agents. There is a great interest in the detection of drugs and explosives. Here, THz techniques have high potential as resonant states are available allowing the spectroscopic distinction of explosives and drugs. In combination with the ability of THz radiation to pass through many materials that are opaque in the visible region (e.g. clothing, plastics and paper), terahertz sensing is a promising tool for security applications.

Development for terahertz imaging applications would proceed through the coupling of THz detection with a THz source implemented for security purposes, including hyperspectral imaging of proximity targets. This could include luggage and mail scanners that seek to pinpoint hazardous materials during the mass transit of people and items. This is an area in which there are numerous existing companies that offer products, ranging from start-ups to multinational corporations. As a critical area in the overall growth of the terahertz market (Reaching ~$40m per annum by 2021 as shown in Figure 4), it is expected that this will become a highly competitive yet potentially lucrative sector. A far-reaching goal in this application area would be to establish stand-off imaging capability that could make use of heterodyne detection scheme.

Statistics of inquiries in 2015/2016 confirms a dramatically increasing demand for security application of terahertz technology like full or partial body scanner and security screening because the technology is capable of undertaking tasks unobtainable for other technologies due to the specific properties of the terahertz waves. Currently used security screening systems like X-ray machines, metal detectors or millimeter-wave scanners have certain limitations and thus can not be used as a versatile solution for detection of concealed weapons and hidden explosives. Metal detectors can only detect metallic objects. They identify all the metal objects without differentiation. Ceramics, plastics, polymers are not visible by X-rays. The screening object must be in the immediate vicinity of the detector, which relates to all of these 3 technologies. Although, the backscatter X-ray machines are considered to use 'soft' X-rays, you are still dealing with ionizing type of radiation. And while the X-ray systems are very expensive, millimeter-wave scanners cost a lot more. THz imaging offers significant advantages over competitors including:

- No ionizing radiation. Absolutely harmless to people, thus can be used in all public places. No special usage permits needed
- Detection distance up to 10 m (in perspective up to 25-30 m). One of the main advantages of the terahertz system is the possibility of distant detection of hidden objects
- Ceramics, plastics and polymers are transparent in terahertz waves, allowing for their internal structures to be imaged, which is useful for non destructive testing and quality control such as that used in the pharmaceutical industry
- Devices are compact and can be easily integrated into any other systems used by customer.
- Unprecedented scanning speed. Image acquisition rate is up to 5000 frames per second, which gives an opportunity to use the scanner at conveyor lines with belt running speed up to 15 ms^{-1}. This figure is of interest to airports, international courier companies and customs terminals. Scanning speed of the world leading X-ray system is 0.2 – 0.23 ms^{-1}. We offer the 75 times higher scanning speed.
- Low cost. Price of our prototype THz imaging system (sub-THz imaging camera, generator and optics) is around £27k. Price of a basic imaging system of a world leading X-ray manufacturer starts at £70k.

THz imaging has been demonstrated to be:

- Capable of detecting and identifying hidden explosives materials in an automated fashion without operator interpretation.
- Safe for screening people to detect metallic and non-metallic objects through clothing and other materials.
- Capable of investigating the contents of envelops and paper packages without opening them.
- Capable of the detection of noxious or dangerous gases such as hydrogen cyanide and ammonia.

3.7 Security Screening Market

The global security screening market is expected to reach $9.10 billion by 2020 with an expected CAGR of 9.46% from 2014 to 2020 (Ref: Security Screening Market, September 2014, AS 2320, marketsandmarkets.com). Homeland security is a top priority in western countries, and is expected to reach 11% per annum market growth. The security screening market involves the scanning of individuals and their belongings, to avoid unlawful and unethical practices. The importance of security screening has been increasing due to threats related to terrorism and other illegal activities, which may result in economic, financial, and human loss.

The market is segmented on the basis of applications, products, and geography. In terms of applications, the security screening market is divided between airports, government applications, border check points, educational institutes, private sector and public places, among others. In terms of the products the screening market is divided into X-ray screening systems, explosive trace detectors, electromagnetic detectors, and biometric systems.

The transportation sector, which includes airports, is the largest representing 38% of total sales. The airport security market is expected to grow in response to:

- Projected growth in air traffic;
- New security threats; and
- Customer pressure for faster throughput at checkpoints and an improved passenger experience.

The critical infrastructure market is diversified with varying growth rates in the different segments. The ports and borders market is a rapidly expanding sector driven by government objectives of enhancing security screening and protecting tax revenues. Customers require mobile and fixed units capable of detecting explosives, weapons, radioactive materials, narcotics and contraband.

North America has been identified as the leader in the market in terms of the market size, with the U.S leading the way. Europe is a promising market, with notable demand in Germany and the U.K.; while the ROW also represents a driving factor toward the growth of this market with Brazil and Argentina. The major players in the security screening market are American Science and Engineering, Inc. (U.S.), Analogic Corporation (U.S.), Argus Global Pty Ltd (Australia), Aware Incorporation (U.S.), Digital Barriers plc. (U.K.), Implant Sciences Corporation (U.S.), Magal Security Systems Ltd (Israel), OSI Systems, Incorporation (U.S.), Safran SA (France), and Smiths Group plc. (U.K.).

3.8 THz-enabled Biomedical Imaging

The biomedical sector for terahertz sensing is expected to see rapid growth in the next 10 years, reaching ~$145m per annum by 2021 as illustrated in Fig. 3. This is another quite diverse sector with a number of fragmented applications, each requiring different technological specifications to meet the technical and regulatory requirements for product development. The greatest potential for this sector is in fully-fledged imaging systems, moving beyond the simpler point detection systems. The most notable sub-sectors are in dermatology and oncology where cancerous markers can be safely observed with non-ionising radiation. Here, there is a clear requirement for a 2D image to be created for effective diagnosis. Numerous groups have now demonstrated medical applications in breast cancer, colon cancer, burn imaging, and corneal hydration. The challenges associated with the type of high-resolution and high-accuracy spectral imaging required and the regulatory environment surrounding any medical applications will make this a slow but still potentially lucrative market to access.

There are also numerous applications in the field of biomolecular sensing where THz systems enable a direct resonant probing of biomolecules and biomolecular binding events. This allows for detecting, identifying and understanding the function of biomolecules with a higher quality than with existing approaches.

There is significant potential for THz imaging in medical markets due, in part, to its ability to recognize spectral fingerprints, provide good contrast between different types of soft tissue, and deliver a sensitive means of detecting the degree of water content as well as other markers of cancer and other diseases. THz imaging has been used to image basal cell carcinoma (a common form of skin cancer) invisible to the naked eye. The ubiquitous presence of such markers in tumors could lead to THz imaging being applied to a number of different cancers like breast, as well as other diseases in medicine, oral health care, and related areas.

THz imaging allows high-resolution subsurface imaging of tissue. It combines macroscopic and microscopic imaging that potentially allows the precise margin delineation of cancer tissue. Due in part to its ability to recognize spectral fingerprints, THz imaging provides good contrast between different types of soft tissue and is a sensitive means of detecting the degree of water content as well as other cancer markers. THz imaging could aid surgeons in differentiating between cancerous and non-cancerous tissues.

It is estimated that more than 85% of all cancers originate in the epithelium. Excision biopsy to remove tissue from the body and examining it under a microscope is the gold standard for cancer diagnosis. THz imaging technology has the potential to greatly improve conventional biopsy and associated surgery by more precisely identifying the areas to be excised thereby reducing the number of procedures and facilitating earlier and more accurate diagnosis. As the technology matures, it may be possible to perform biopsies using THz imaging alone, making possible point of care optical biopsy.

Uniquely THz imaging offers the ability to produce 3D images at high resolution through thick tissue using molecular markers, such as water, to provide spectral and absorption information to differentiate between cancerous and non-cancerous tissues, non-invasively and using non-ionising radiation. THz imaging is non-ionising and less hazardous to use than X-rays and the power levels are generally lower than background terahertz radiation encountered in everyday life. THz imaging can aid in: earlier detection of epithelial tumours, reduced treatment costs and lower morbidity rates.

3.9 Medical Diagnostic Imaging Market

According to a report by Marketsandmarkets (Ref: Diagnostic Imaging Market, February 2017, MD 2367, marketsandmarkets.com) the global diagnostic imaging market is expected to reach $33.42B by 2020, at CAGR of 6.2% from 2015 to 2020. A number of factors such as rising prevalence/incidence of cancer and cardiac, neurological, and musculoskeletal disorders; rise in awareness for early diagnosis; and growing number of diagnostic imaging procedures have increased the demand for imaging systems in healthcare facilities across the globe. Moreover, improving healthcare infrastructure in emerging markets and low-cost, technologically advanced imaging systems with applications in multiple fields are further stimulating the demand for diagnostic imaging, globally.

As of 2015, North America holds the largest share of the global diagnostic imaging market, followed by Europe. However, the Asia-Pacific market is expected to grow at the highest CAGR of 7.2% from 2015 to 2020. A number of factors, including increasing incidence of chronic diseases, rising awareness about the benefits of early disease diagnosis, development of new healthcare facilities, growing medical tourism in APAC countries, and increasing government initiatives for the modernization of healthcare infrastructure, are stimulating the growth of the diagnostic imaging market in the Asia-Pacific region.

GE Healthcare (General Electric Company, U.K.), Siemens Healthcare GmBH (Siemens AG, Germany), Koninklijke Philips N.V. (The Netherlands), Toshiba Medical Systems Corporation (Toshiba Corporation, Japan), Hitachi Medical Corporation (Hitachi Ltd., Japan), Carestream Health, Inc. (U.S.), Esaote S.p.A (Italy), Hologic, Inc. (U.S.), Fujifilm Corporation (Japan), Samsung Medison (South Korea), and Shimadzu Corporation (Japan) are the major players in the global diagnostic imaging market.

3.10 THz Imaging for Pharmaceutical Quality Assurance

The proposed THz imaging would enable effective monitoring of a wide range of pharmaceutical products for the purposes of counterfeit detection and chemical composition verification. THz imaging can be used to non-destructively estimate critical quality attributes in pharmaceutical products such as crystalline structure, thickness and chemical composition. The approach can monitor chemicals or active ingredients during pharmaceutical manufacturing and sense chemical spatial distributions. The use of Rydberg THz technology for pharmaceutical testing application is a highly compelling solution for a large industry with critical quality assurance tolerances.

Pharmaceutical tablet coatings control the release of active pharmaceutical ingredients to ensure the bioavailability, safety and efficacy of the drug product. These functions may be severely compromised if a coating is non-uniform or has defects. From this standpoint, it is critical to assess coating integrity in coated tablets, both within a single tablet and across an entire batch to ensure product quality and monitor and control coating operations.

THz imaging provides the ability to non-destructively and rapidly analyse the coating layer thickness and quality of coated pharmaceutical tablets. Because it is non-destructive, tablets can be re-examined at later times to monitor coating stability or used for further functional studies with prior knowledge of the coating uniformity.

THz imaging allows: rational product design and control, ensures ICH (International Council on Harmonisation) compliant product registration, mitigates risk of product failure and optimises manufacturing costs. Such systems are able to: detect density variation in tablet cores, identify crack propagation leading to tablet failure such as capping and delamination, monitor coating thickness, density, integrity and uniformity and monitor interaction between multiple coatings or core layers.

THz imaging can rapidly identify the different crystalline forms of drug molecules, the polymorphs, which can display different solubilities, stabilities and bioavailability and therefore are an important factor in the therapeutic efficacy of a drug. Not only is it possible to detect the differences between pure specimens of the polymorphs but also terahertz spectroscopy can distinguish between specific polymorphic forms in the tablet formulation.

THz imaging can differentiate between different hydrate forms. Lactose, one of the most commonly used excipients in the pharmaceutical industry, forms at least three different hydrates: the most widely used a-monohydrate, the α-anhydrate and a β-anhydrate form. These three hydrate forms exhibit terahertz spectra that can be used for both quantitative and qualitative analysis. The terahertz region also provides unique sensitivity to lattice structure enabling qualitative and quantitative analysis of crystalline and amorphous materials.

3.11 THz Imaging for Near Field Microscopy

The very first demonstration of THz imaging clarified that microscopic resolution is required for applications ranging from semiconductors inspections to biomedical imaging. For a corresponding wavelength at 1 THz, however, the far-field spatial resolution of an image is restricted to the Rayleigh criterion that corresponds to ~180 μm in vacuum. To overcome this limit, the near-field region must be accessed. In this case, the THz wave has to be captured very close to the sample surface in a region before light diffraction occurs. Many schemes have been proposed since the first demonstration of THz near-field imaging, most of which involve a subwavelength probe or an aperture placed very near the sample

However, even if spatial resolution below 10 μm is successfully achieved at THz frequency, all of the traditional schemes remain based on raster scanning techniques. In such cases, the imaging acquisition time associated with optical scanning techniques is relatively long and quadratically increases as a function of area size (i.e., a few hours for a 600 x 600 μm scan with 20-μm spatial resolution). Ideally, to map in real-time the morphological changes of such sub-wavelength structures as cells or microorganisms, a new approach with a faster acquisition time is required. The presented RQT THz imaging solution fits this role and provides a unique selling point of the approach unrivalled by current state of the art. The ability to scan instantaneous at near video rate full 2D images is a significant advancement over the existing microscopy techniques. Near-field scanning optical microscopy (NSOM/SNOM) is the current state of the art microscopy technique for nanostructure investigation that breaks the far field resolution limit by exploiting the properties of evanescent waves. This allows for the surface inspection with high spatial, spectral and temporal resolving power, yet is limited due to its long scan time based on raster scanning.

3.12 Scanning Probe Microscopy Market

According to a report by research and markets (Ref: The Global Market for Scanning Probe and Electron Microscopy, October 2014, futuremarketsinc.com) the scanning probe microscopy market in 2014 generated approximately $450-$505 million in revenues. Main players in the market are Keysight Technologies, Bruker, JPK and Asylum Research, NT-MDT, Hitachi High-Tech Science Corporation and Park Systems. These companies have the greatest global market presence and their instruments are most widely used. Bruker has the largest market share in AFM.

The AFM market grew in semiconductors due to investment in capacity growth and the overall strength in the semiconductor market. In the last quarter of 2014, growth was witnessed in the US and Asia Pacific (especially China). In the first half of 2015 there has been a strengthening of the market for nanotechnology tools in the US. One such area of nanotechnology seeing substantial growth is that of the metamaterials (shown below), and is likely driving growth for scanning probe microscopy.

Advanced techniques such as scanning probe microscopy make up a significant proportion of the microscopy market. Market drivers for advanced microscopy include the increase in the complexity and performance level of devices used in electronic products, reduction of manufacturing costs, increased resolution, increasing device complexity and shrinking geometries in materials research. The scanning probe microscope markets witnessed moderate growth in 2013. Market conditions have improved in 2014, with some companies seeing strong demand for their products, with growth of 3-9%.

The North America advanced microscopy market is considered mature. Developing Asian markets such as China, Korea, India, and Taiwan are experiencing good growth. The developments in nanotechnology, material science and life sciences, heavily backed by government investment, drive interest in advanced microscopy, in addition to the improvements in software design and increased degrees of automation in end-user industries.

3.13 Metamaterials Market

According to a report by Grand View Research (Ref: Metamaterials Market, April 2014, SE 2430, marketsandmarkets.com) the global metamaterials market is expected to reach $62 bn by 2024 with an expected CAGR of 25% from 2016 to 2024. Metamaterials are widely used in the telecommunication and medical fields. These materials possess artificial electromagnetic properties. The rare properties of metamaterials have led to the development of metamaterial antennas, sensors, and lenses for minute wireless systems that are expected to be more efficient than other traditional systems. They exhibit a sensitive response to dielectric media, strain, biological sensing applications, and chemicals.

Metamaterials are artificially engineered materials to provide unique advantages over other conventional substitutes owing to properties that are not readily found in nature. They gain their distinctive properties from the structure of the homogeneities infused in them.

The growing demand for graphene-based metamaterials in the medical field is estimated to drive the market growth over the forecast period. Need for implementing wireless telemetry systems in the medical field is expected to increase significantly owing to the necessity for early diagnosis of infections or diseases and continuous intensive care monitoring of physiological parameters. Sensors and microwave antennas are major components of telemetry systems since they provide communication between the base station and patient. Metamaterials show electromagnetic properties at frequencies, which are expected to attract interest from physicists and microwave engineers. These factors are anticipated to drive the market growth and provide a potential base for commercial development of metamaterials over the next seven years.

The global metamaterials market is driven by surge off-grid solar power system demand, to improve the efficiency of photovoltaic cells and increasing investments by venture capital firms in the market. Metamaterials absorb a broad range of light with exceptionally high efficiency, which is expected to increase applications for optical sensors and solar cells. These materials are fragile, saving weight and cost. Rising demand and awareness of benefits that solar cells provide to generate energy is expected to drive this technology. A lack of customer awareness about the advantages of metamaterials is expected to pose a significant challenge to the global market growth over the next few years. Technical complications coupled with high cost and time taken for the development cycle can be attributed as significant challenges to the industry growth.

Based on the metamaterial types, the global market has been segmented into terahertz, acoustic, photonic, microwave and radio metamaterials. Other types include infrared and ultraviolet metamaterials. Microwave and radio frequency electromagnetic metamaterials are expected to contribute the largest market share owing to increase in wireless broadband, mobile communications and technological advancements in communication infrastructure. Key players operating in the global metamaterials market include Applied EM, Kymeta, Teraview, Plasmonics Inc., JEM Engineering and Microwave Measurement Systems LLC. Other industry participants include Harris Corporation, Newport Corp., and Photonic Lattice Inc, Applied EM introduced tiny form factor antennas that reliably perform at low voltages and also developed enhanced electromagnetic simulation tools using asymptotic computational techniques.

3.14 Nanometrology Market

Nanometrology is a subset of metrology, which is concerned with the science of measurement at the nanoscale level. Nanometrology has an important part in order to produce nanomaterials and devices with a high degree of accuracy and reliability in nano manufacturing. A challenge in nanometrology is to develop or create new measurement standards and techniques to meet the needs of next-generation advanced manufacturing, which will rely on nanometer scale materials and technologies. The requirements for estimation and portrayal of new specimen structures and attributes far exceed the capabilities of current measurement science. Foreseen advances in emerging nanotechnology industries will require revolutionary metrology with high determination and accuracy that has previously been imagined.

The nanometrology sector in Europe is expected to be one of the leading geographic markets, due to explosive growth in recent years for related applications. The research and development and number of application in nanonetrology keep on growing in the coming years. With the versatility of application nanometrology is being used efficiently. The Service National Standards of the FPS Economy plays an essential role in the growth, through specific projects assigned to nanometrology as well as through on-going research into the best possible efficiency of physical measurements. In impact, on a nonmetric scale, the accuracy of temperature measurements or measurements of electricity or pressure determines the accuracy of the dimensional measurements themselves. The demand for nanometrology will experience a boom and move towards maturity where the sustained markets will be established.

The major players in this sector are: Accu-scope, Leica, Olympus, Glenammer, Keison, Precision Eforming. The market is segmented on technology between XPS (X-Ray Photoelectron Spectroscopy), Raman spectroscopy, photoluminescence and electroluminescence spectroscopy. The segmentation based on application covers: energy industry, food industry, computer science industry, transport industry and others. Product segmentation follows the main groups of: microscopes, practical size analysis equipment, sieves, chemical characterization, surface area analysis equipment and others.

4 MICROWAVE REGIME

4.1 Microwave Sensor Competitor Analysis

The proposed Rydberg system has many of the benefits already described for the THz regime in the microwave regime. Although microwave technology is has been extensively developed and implemented the proposed Rydberg system has several notable advantages which have been listed in a comparison table in Table 4 below. The Rydberg approach is costlier, in the £1000's region, than £100's of microwave horn or antenna approaches, but less than bolometers that are require a bulky and complex cryogenic cooling stage. The main advantages of the RQT methods are: having a very broad tuning range possibilities, a lack of calibration requirement, it's spectrally resolved, capable of measuring THz region and has the potential for very small millimetre form factors. Bolometers are also capable of broad tuneability and of therefore reaching THz regions.

4.2 Microwave Technologies

Microwave technology is a well-established field that occupies many applications, from food preparation to the search for extra-terrestrial intelligence. For the sake of simplicity and sanity, we'll consider microwave as primarily a communications technology (wireless 3G, mobile phones, defence, etc.). Microwave imaging has been proposed, studied, and implemented to varying degrees by a plethora of worldwide institutions for the last 30 years. This is due to the versatility and suitability of this imaging technique for a wide range of applications. For example, in the non-destructive evaluation (NDE), microwave imaging (MWI) has been proposed for online testing of material, in particular, the detection of possible defects and measurements of physical quantities

Table 4: Comparison table of the main classes of microwave detector

Technology	Microwave Horn	Conventional Antenna	Bolometer	RQT
Cost	10 's	100's or less	as above	1000's
Single device frequency range	1-20 GHz possible, depends on design wavelength, 10's of GHz typical	3% of centre wavelength, log periodic (approx. 20 GHz)	Can be broadband as above	From THz to sub-GHz
Requires calibration?	Yes	Yes	Yes (relative measurement)	No
Spectral discrimination	No	No	No	Yes
THz capable?	No	No	Yes	Yes
Size of detector element?	Dependent on cut-off frequency, 10's of cm for 10 GHz cut-off	Same as the microwave horn	Cryogenic devices extremely large	Millimetre scale fibre-coupled packages possible
Comments	Lent to high frequency directionality, unwieldy at low frequencies		May require cryogenic cooling	

(e.g. moisture content) on conveyed products. It also can be used for material characterisation, such as the determination of constituent, evaluation of porosity, and assessment of the curing state. In military applications, microwave's ability to penetrate into dielectric materials makes them useful for interrogating military composites. In aerospace applications, MWI may be useful for the detection of cracks that may occur in aircraft components and structures. In the geographical prospecting field, MWI has been used in remote detection of subsurface inclusions such as tunnels, landfill debris, and unexploded land mines. In civil and industrial engineering application MWI can be useful for evaluating the structural integrity of roadways, buildings and bridges. Microwaves have been shown to be able to image objects concealed beneath clothing in the areas of security imaging. In medicine, currently, MWI systems have been proposed for non-invasive biological imaging applications. Significant progress in MWI has been accomplished in the last decade, with experimental prototypes capable of imaging excised pigs legs, heart disease such as ischemia and infraction, breast cancer imaging, brain imaging, bone imaging, and detecting ischemia in different parts of the body.

Microwave detection, and imaging, is possible using the identical setup as described for THz detection in Section 2. Here a different state can be addressed. The signal strength will be different dependent on the choice of atomic gas and transitions targeted. Signal strength can as such be tailored. Since the method is identical all previously discussed features of the approach are relevant. The system would be frequency resolved and deliver an intensity measurement, along with instantaneous microwave imaging. This implies that the Rydberg gas cell can be used for near and far field microwave imaging, for which the markets are described in Section 2. A key problem with MWI is the computational reconstruction of the complex microwave signal from the high degree of field scattering involved with electromagnetic fields.

4.2 Advantages of Rydberg Quantum Technologies

A stated goal of international metrology organizations, including the National Institute of Standards and Technology (NIST), is to make all measurements directly traceable to the International System of Units (SI). Measurements based on atoms provide such a direct SI traceability path and enable absolute measurements of physical quantities. Measurement standards based on atoms have been used for a number of years for a wide array of measurements; most notable are time (s), frequency (Hz), and length (m). There is a need to extend these atom-based techniques to other physical quantities, such as electric (E) fields. To date, all methods to make an E-field measurement that is SI traceable requires a complex traceability path. The RQT technique presented provides a much more direct traceability path. There is also a pressing need to have physically small probes that are not only self-calibrating but can also perform measurements on a small spatial scale (i.e., sub-wavelength), as well as performing near- and far-field mapping and imaging.

There is a push from various international metrology laboratories (including the National Institute for Standards and Technology, NIST) to make all measurements traceable to SI units and/or traceable to fundamental physical constants. While, a large number of various measurements are SI traceable, to date, all methods to make an E-field measurement that is SI traceable requires a complex traceability path.

Possible applications for this probe are numerous, ranging from biomedical to sub-wavelength imaging. Unlike conventional microwave antennae, where structural elements need to be fabricated on the scale of the wavelength, RQT solutions can be considered 'future proof', as sensitivity in the THZ regime, as well as microwave regions, have already been demonstrated. (See Wade 2016 paper)

This new approach for E-field measurements has the following benefits:

1) It yields the field strength in SI units from a frequency measurement, fundamental constants, and known atomic parameters

2) It is self-calibrating due to the invariance of the atomic parameters

3) It will provide RF E-field measurements independent of current techniques

4) Since no metal is present in the probe, the probe will cause minimal perturbation of the field during the measurement

5) It will measure both very weak and very strong fields over a large range of frequencies (field strengths as low as 0.8 mVm^{-1} have been measured, and below 0.01 mVm^{-1} may be possible)

6) It allows for the construction of small, compact probes (optical fiber and chip-scale probes)

4.2 Overview of Electro Magnetic Compatibility (EMC) Testing

Electromagnetic inference (EMI) is caused by the unintentional generation of electrical signals by electronic equipment. This interference can harm people and even cause equipment to malfunction depending on its strength. It is important to keep equipment electromagnetically compatible with the environment and other equipment to mitigate pollution caused by EMI. Equipment intended for free trade across the European Union should achieve the "Conformité Européenne" and carry the CE mark of certification, as governed by a set of regulations comprehensively covered in EMC Directive 2004/108/EC. Only equipment bearing the CE mark can be bought and sold inside of Europe.

EMC (Electro Magnetic Compatibility) is the metric by which the electromagnetic noise from a product is tested. Different regions have different regulations regarding EMC (e.g. FCC for the US, EC for Europe and CCC for China), but all follow the same principle- the electromagnetic leakage from devices should be restricted in order to limit the background electromagnetic noise level. The history of EMC is a long one, rules covering the interference of electronic devices with telegraph lines were established in Germany towards the end of the 1800's, as were rules covering 'flicker' in arc lamps in London. Nowadays EMC is regarded to cover noise throughout the entire electromagnetic spectrum transmitted through free space, in addition to inductive/capacitive coupling through conductors. It is worth noting that EMC testing also covers 'immunity', the ability for equipment to operate in a shared (i.e. imperfect, noisy) environment without failure. As Rydberg type detectors have limited impact on this segment of EMC testing, it will not be discussed further. As an aside, there is a surprisingly high level of non-compliance with EMC regulations, one investigation within the EU finding a 91% non-compliance rate of equipment under test.

The accurate measurement of electric fields is important for a host of applications, especially at microwave frequencies. Perhaps most importantly, the ability to sensitively measure microwave electric fields can allow for the amplitude stabilization of a microwave electric field source and the determination of optical properties of materials at these frequencies to high precision.

4.3 Current EMC Approaches

The very core of all electromagnetic measurements (i.e., antenna characterization, propagation measurements, and channel modelling and measurements) is having accurate calibrated probes and antennas. Calibrating an electric (*E*) field probe and/or measuring an *E*-field can be challenging, and is somewhat of a chicken-or-egg dilemma. In that to calibrate a probe, one must place the probe (sensor) in a "known" field. However, to know the field we need a calibrated probe. One example consists of a diode placed across a dipole antenna. The output of the diode is connected to a DC voltmeter via a high-impedance line (on the order of 1,000 $k\Omega m^{-1}$). When placed in an *E*-field, the diode rectifies the electromagnetic (EM) field and the DC voltage is recorded. This DC voltage increases or decreases with an increasing and decreasing electromagnetic field strength. To use this dipole probe, it first must be calibrated, which involves placing the probe in a known (calculated) field.

For microwave electric field sensing, then, a major limitation is the antenna, as it is the converter of the microwave electric field to some observable, for example voltage, and depends on geometry, can lead to perturbations of the microwave electric field, particularly in the near field, and can suffer from out-of-band interference. The optical detection system is subject to ageing and manufacturing variations.

Figure 4: Example of an anechoic chamber. Ref: TUR-CERT

The combination of very small dipole antennas, and diode detector circuits connected to resistive lines and high-impedance voltmeters, requires substantial E-field strength for reliable measurements. While fields can be detected in the range of 100 mVm^{-1} the amplitude uncertainties can be large. The useful sensitivity (minimum field strength) is typically on the order of 500–1000 mVm^{-1}. While the probes can in principle be electrically small (with the caveat that the sensitivity decreases as the probe size becomes smaller), the limiting factor on the overall size of the probe is due to both the electronics in the probe head and the size of dipole antenna required to drive the current across the diode. This type of probe has been used for over 40 years and has the following limitations:

1) It needs be to calibrated

2) The sensitivity of the probe is governed by the dipole length

3) The metal in the probe perturbs the field being measured

4) The sensitivity of the probe is limited to a minimal detectable field strength of 100 mVm^{-1}

The most common way to generate a known field is to perform a measurement in an anechoic chamber (AC) or other type of test facility. For an AC configuration, the probe is placed at a known distance (1-3 m) from an antenna and Maxwell's equations are used to calculate the field strength. Due to the uncertainties in this approach, the "known" field is only typically known to within 5% (or 0.5 dB). Thus, common E-field probes in use today have many shortcomings: they are not very sensitive, may perturb the field during the measurements, may be relatively large, and require a calibration. The calibration procedure relies on a field value that is known to within only 5%.

4.4 Rydberg Quantum Technologies for EMC Testing

Traditional EMC testing is performed by observing the emitted radiation of Equipment Under Test (EUT) with an antenna in the far-field. The EUT or antenna is rotated such as to examine the directionality of the emitted electromagnetic radiation. In order for the test to be meaningful, the antenna is calibrated against a 'known source'. The 'Known Source' is calibrated by some other means. The RQT discussed forgoes the calibration step of traditional sources; the electric field measurements performed by the RQT are directly traceable to the immutable physical properties of the atom. To this end, RQT can be used as a self-calibrating probe, eliminating some potential systematics in the EMC test process. Additionally, the RQT can be used to calibrate other probes, and as discussed above, retains this self-calibrating behaviour into the THz region.

While EMC regulations are necessarily expansive, it is beneficial to examine the general trends and patterns relating to the MW bands and above. As more and more devices occupy the higher frequency bands (mobile phones, GPS systems, etc.) testing and regulations in this area have had to increase the scrutiny afforded to these regions.

Additionally, the upper tested frequencies required for EMC tests are related to the clock speed of the device under test. With the advent of the Internet of Things and the proliferation of high-speed processors in formerly 'dumb' products (watches, wearables etc.) extensive EMC testing at higher frequencies is very likely

4.5 Electro Magnetic Compatibility Market

Sometimes perceived as a necessary evil, the test and measurement industry plays a critical role in the delivery of product and service quality to one's customers. Virtually every industry, including aerospace and defence, telecommunications, automotive, energy, medical, consumer electronics, semiconductors and many more, uses test and measurement equipment for designing, manufacturing, deploying and ensuring the highest level of satisfaction of customers with products and

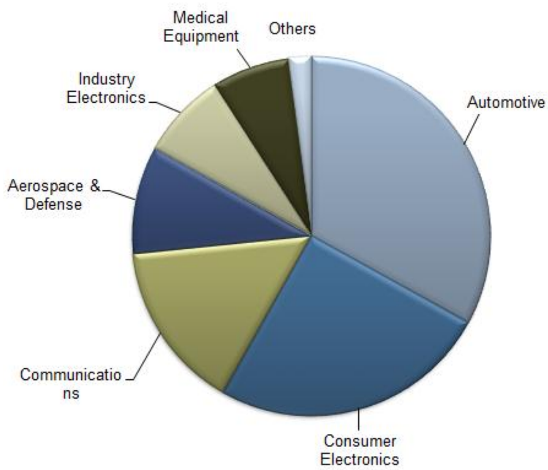

Figure 7: EMC test services market segment: Percent of revenue by end-user. Ref: EMC Market report 2014, Frost & Sullivan.

services.

The European electromagnetic compatibility (EMC) market can be segmented into three very broad areas: EMC testing service providers, EMC test and measurement equipment manufacturers, and manufacturers of other devices that make products electromagnetically compliant such as filters, capacitors, connectors, and RF chokes.

Test & Measurement Key Issues:

- Increasing complexity of devices to be designed, produced and deployed by manufacturing companies is requiring an unprecedented level of knowledge from the users of test equipment
- Increasing industry maturity in developed regions demands a change in customer reach strategies for market participants
- The economic downturn of 2008-2009 is still impacting the test strategies of customers, forcing companies to look beyond selling capital equipment and consider alternative ways of acquiring test equipment

According to new analysis from Frost & Sullivan (Ref: The European Electromagnetic Compatibility Testing Equipment and Test Services Market, May 2014, M9DE-01, frost.com) the rapidly growing electric vehicle sector to give a fillip to the EMC test and services market. The wider integration of wireless technology into products that were previously wired has caused a steady shift in electromagnetic compatibility (EMC) test services from classic or non-wireless testing to wireless testing. This trend, along with the proliferation of smart devices, has resulted in a higher number of new frequency bands. The greater density of frequency bands, in turn, has created a need for noise and emission reduction, making a strong case for enhanced EMC tests and services.

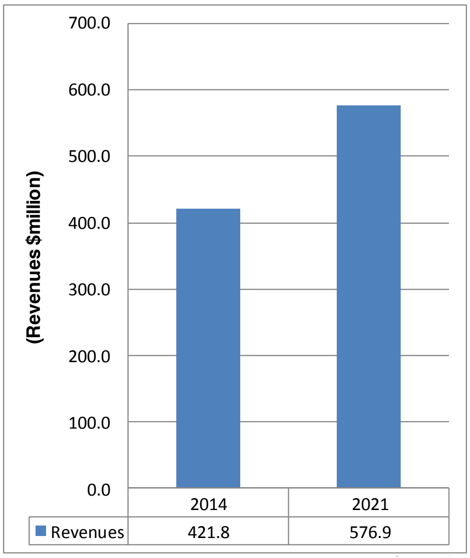

Figure 8: EMC testing Equipment and Test Services Market, Europe, 2014 and 2021. Ref: EMC Market report 2014, Frost & Sullivan.

The European Electromagnetic Compatibility Test and Services Market, finds that the market earned revenues of $422 million in 2014 and estimates this to reach $576.9 million in 2020, growing at a CAGR of 4.6%. Other drivers for the European EMC market include new enhancements in wireless communications and its integration into segments that were not wireless previously. This trend is expected to increase frequency bandwidth and therefore noise and interference affecting the EMC business positively as there would be a higher requirement for EMC test equipment and testing services.

It is anticipated that with the integration and implementation of new technologies as well as the increasing complexity of electronic equipment, customers will require enhanced types of testing services. Consequently, there will be the demand for EMC test equipment such as electromagnetic interference (EMI) test receivers, which are capable of more and quicker measurements, and spectrum analysers that are faster as well as more efficient and versatile.

Furthermore, the advances in the automotive industry will sustain the market where there is intense activity around electric and hybrid vehicles. Electric and hybrid cars consist of a high voltage power source, an electric motor, a frequency convertor as well as high power cables. The high voltage power source could lead to more emissions of radiation, which can pollute the environment, or interfere with other electric equipment. To ensure that the vehicle is electromagnetically compliant with its surroundings, original equipment manufacturers (OEMs) require EMC testing services and consultations from a market participant with significant expertise in this domain. Overall, the higher sophistication of electric and hybrid vehicles generates a need for upgraded EMC test equipment and systems. This is a relatively new growth driver to the EMC market and would require these companies to establish new labs and invest in new equipment and new standards for measurement. Another drive is the growing market in Eastern Europe. Many companies in this region are trying to enter the European market. They would therefore have to certify their products according to the standards set forth by the European Union.

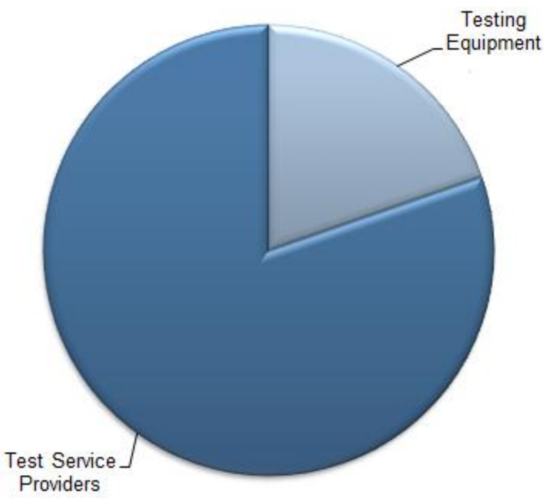

Figure 8: Revenue percent split between testing equipment and test services market segments. Ref: EMC Market report 2014, Frost & Sullivan.

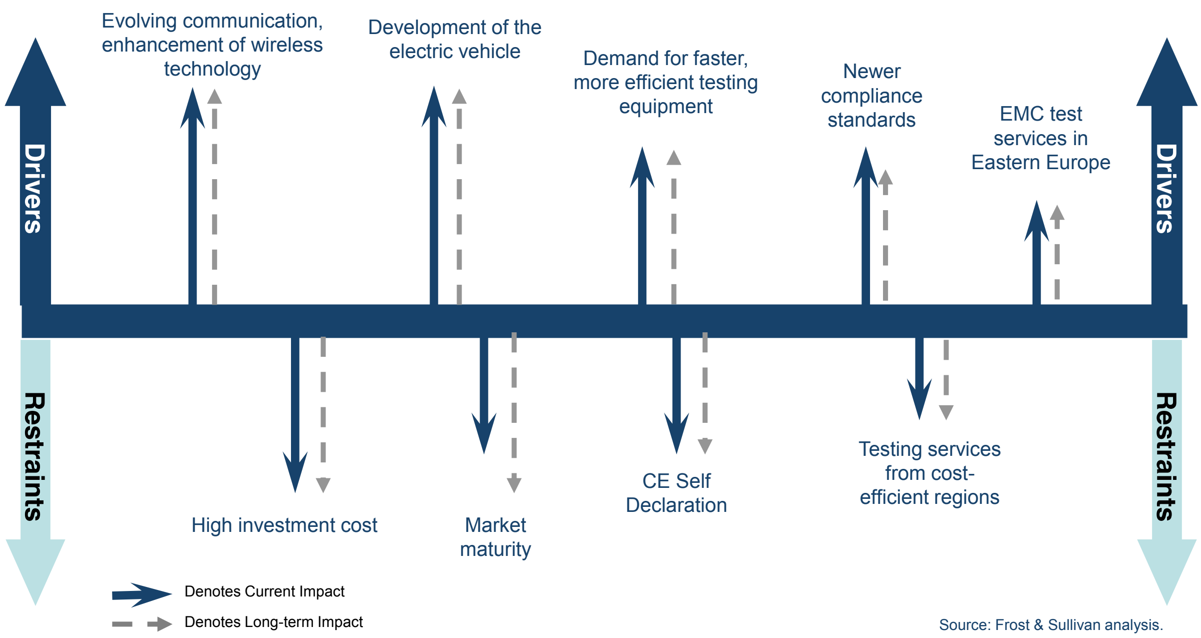

Figure 9: EMC Testing Equipment and Test Services Market: Key Market Drivers and Restraints (Europe), 2014-2021. Ref: EMC Market report 2014, Frost & Sullivan.

One could expect to witness more demand for EMC testing service providers as well as EMC testing equipment as a result.

Although opportunities are plenty, the maturity of the market hinders the growth of smaller participants. As suppliers of EMC testing equipment and test services build their reputation on experience as much as technical expertise, it will be difficult for a market entrant to break into the market. The high investment costs are also significant entry barriers to a fragmented and price-sensitive market. It is regarded that in such a scenario, participants tend to pull out all stops to retain their customer base - primarily by providing exceptional customer services and international standards of testing. As EMC testing equipment and test services are highly specialized, participants have to constantly offer technological innovations and act as one-stop shops for customers.

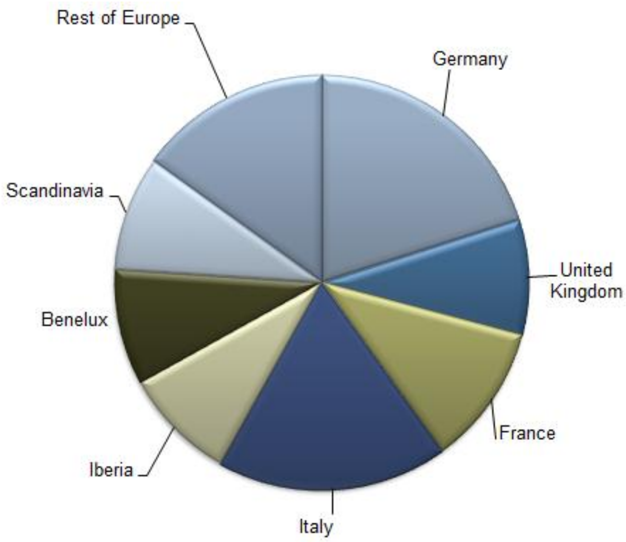

Figure 10: EMC testing equipment and test services market: Percent of revenue by country. Ref: EMC Market report 2014, Frost & Sullivan.

Additionally the EMC market in Europe is very well established and highly regulated. Some experts also believe that unlike the previous decade and its considerable growth, the EMC market has reached a plateau and will not witness tremendous growth anymore. The market is mainly sustained by the introduction of new and innovative products that need to be certified against regulations specified by the European Commission. The RQT approach will also face this regulatory approval requirement however a market also existing for in house unregulated testing exists.

The European Electromagnetic Compatibility testing service providers segment, unlike the test and measurement equipment segment is very fragmented. It consists of in-house laboratories and independent companies that provide EMC testing for OEMs of a broad range of products involving electronics. Companies like Fujitsu have in-house laboratories and also offer EMC testing services to external participants. Major participants that provide EMC testing services to other companies include but are not limited to Intertek, SGS, Bureau Veritas, Underwriters Laboratories, TUV-SUD, TUV Rheinland, and DEKRAS.

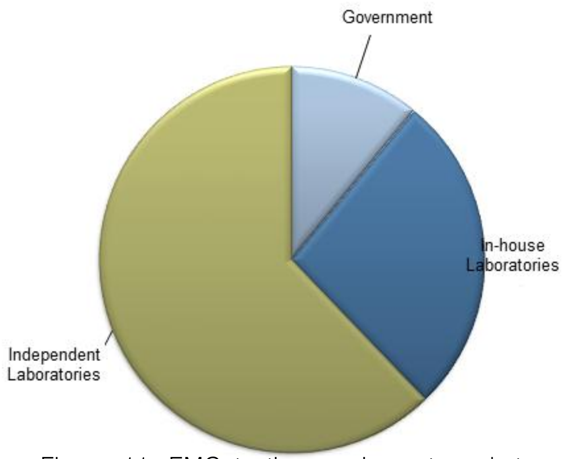

Figure 11: EMC testing equipment market segment: Percent of revenue by end-user. Ref: EMC Market report 2014, Frost & Sullivan.

Some of the most significant participants in the European EMC testing and measurement segment include Rohde & Schwarz, Agilent Technologies, and Teseq AG, along with smaller companies like Frankonia Group, EM Test AG, and Gauss Instruments. Rohde & Schwarz is the leader in this segment in Europe by a very significant margin. In the last few years, there has been a lot of volatility with regard to the number of participants inside this space. For example, companies like Anritsu and Tektronix, which were active some time ago, have left. Agilent Technologies, on the other hand, was momentarily inactive but is now an active participant.

The EMC markets in the UK and France and Italy contribute to about 20% of the European market. Key end users in the UK and France would include aerospace companies, which help sustain the EMC testing and services market

Independent test laboratories are a significant end-user of EMC related testing equipment. With the European crisis bottoming out and the economy promising to pick up, Government spending should show signs of growth. There could be a slight shift with respect to market share of end-users who have in-house facilities, to end-users who specialize in providing third-party EMC test services.

4.7 Microwave Medical Imaging

Widely used medical imaging systems in clinics currently rely on X-rays, magnetic resonance imaging, ultrasound, computed tomography, and positron emission tomography. The aforementioned technologies provide clinical data with a variety of resolution, implementation cost, and use complexity, where some of them rely on ionizing radiation.

Microwave imaging is an alternative method based on non-ionizing electromagnetic signals operating over the frequency range covering hundreds of megahertz to tens of gigahertz. The advantages of using low energy electromagnetic signals are low health risk, low cost implementation, low operational cost, ease of use and user friendliness. Advancements made in microelectronics, material science, and embedded systems make it possible for miniaturization and integration into portable, handheld, mobile devices with networking capability. MWI has been used for tumour detection, blood clot/stroke detection, heart imaging, bone imaging, cancer detection, and localization of in-body RF sources. The fundamental notion of MWI is that it exploits the tissue-dependent dielectric contrast to reconstruct signals and images using radar-based or tomographic imaging techniques.

4.8 Breast Cancer Imaging

The application of microwave imaging to the breast cancer detection problem has singularly motivated the wide-ranging worldwide efforts in this technology. Early detection of breast cancer provides perhaps the best chances for long-term survival rate, resulting in a better than 95% chance of survival for five years or longer. The current gold standard for breast imaging is with x-ray mammography; however, it has numerous risks and pitfalls. Furthermore, these include limited effectiveness for imaging denser breast, the lack of patient safety due to the ionizing radiation, patient discomfort, and especially the inherent imaging ambiguities that regularly result in a large percentage of false positives (which lead to unnecessary biopsies) and false negatives (which miss malignant tumours). Recent advances in microwave imaging show promise for improved detection and diagnosis of small early-stage tumours, due to the distinct electrical contrast of the cancerous tumours with respect to healthy breast tissue. Microwave breast imaging uses low-power radio frequency signals, similar to cell phones. The main challenge in microwave imaging is in converting the rich information content of its measurements to quantitative tissue properties to allow specific diagnostics. This process is called inverse scattering.

4.9 Microwave Device Market

According to a report by Marketsandmarkets (Ref: Microwave Device Market, June 2014, AS 2532, marketsandmarkets.com) the global microwave devices market is expected to register a growth of 3.40%, and reach $1.2 billion by 2019. The global microwave devices market is split by Application (Medical, Space, Defence, Science, Industry, Broadcast Navigation), by Product (Klystron, Thyratron, Travelling Wave Tube, Magnetron), by Geography (North America, Europe, Asia-Pacific, The Middle-East, Latin America, Africa). These devices are essential elements in specialized military, medical, scientific, and space applications, which is also expected to fuel the market growth. Increasing demand from military applications is expected to be a key factor driving microwave devices market growth. Additionally, increased adoption of microwave devices in navigation radar for Unmanned Aerial Vehicles (UAVs) is also expected to positively impact market growth over the next few years. A few major applications include food decontamination and sterilization, which may also drive market growth over the next few years. The major players such as Thales (France), CPI (U.S.), Teledyne (U.S.), L-3 Communication (U.S.) and e2V (U.K) play a major role in the industry. U.S. and Europe are the key players of the microwave industry, in terms of region.

5 CONCLUSION

The Rydberg sensor is a uniquely novel approach to THz and microwave detection promising a transformative and disruptive technology. Currently available THz and microwave detectors fall into broadly three classes: solid-state sensors, which are either cryogenic and highly sensitive (e.g. bolometers) or room-temperature with low sensitivity (e.g. pyroelectric); electronic devices, which have medium sensitivity and bandwidths mostly limited to below 1 THz (e.g. Schottky diodes); and acousto-optic (Golay cells), which have medium sensitivity and slow response time (~10 Hz). The Rydberg detector presents unique detection capabilities by employing a new and innovative approach using photonic interactions within gaseous media to produce a device combining high sensitivity, room-temperature operation, small size, and fast response.

The Rydberg detector has several important advantages that are unique to this device:

- It can operate across a wide range of frequencies, from 1 GHz to 10 THz.
- It can measure both very weak and strong fields (i.e. it does not suffer from saturation).
- The rise time can be as fast as 10 microseconds.

- It can operate by converting field magnitude measurement (which is difficult and has high uncertainty) into highly sensitive and accurate frequency measurement.
- It causes minimal perturbation of the measured field, because it has no parts that are metallic or have a high dielectric constant.
- The measurement is SI-traceable, which is particularly important for metrology.
- The sensor can be miniaturised for field measurements with micron-scale spatial resolution.

The compact room-temperature Rydberg terahertz detector arises from paradigm-shifting science that will lead to new and disruptive capabilities in terahertz sensing and imaging across a wide range of applications; its use will provide significant competitive advantage in a challenging global marketplace.

Rydberg quantum technologies present commercial opportunities for both the terahertz and microwave regimes. In particular metrology type applications that are directly traceable to SI units fills an unoccupied gap in the market with no discernible competitor. This will be immediately exploitable in the microwave detection market for EMC testing. Furthermore, the physical implementation would be simple also. Secondly, the ability to reach beyond the diffraction limit and to image instantaneously will be widely applicable to near-field THz imaging in commercial microscopy applications. Currently microscopy is widely used in semiconductor production and is becoming increasingly important in the field of metamaterials that is expected to experience significant growth in the near future. Thirdly, longer term and large markets can be expected from large scale imaging for security and medical applications. Although longer to develop and with more regulatory needs these sectors have very large exploitable markets potentially displacing x-rays by offering non-damaging spectroscopically resolved imaging. Finally, non-destructive testing and quality assurance applications require imaging developments but have unique capabilities not available by competing systems.

