Chapter 11
Electromagnetic Metrology for Smart Technologies

Part I: Microwave Metrology

S. K. Dubey, Saood Ahmad, C. K. Suman, Sandhya M. Patel, Sudhir Husale, Anurag G. Reddy, Anurag Gupta, and D. K. Aswal

Abstract Electromagnetic (EM) Metrology at CSIR-NPL comprises of various measurement facilities in frequency range from 1 Hz to 110 GHz of electromagnetic spectrum for devices from household electronic appliances to advanced strategic communication and instrumentation. Part-I of the chapter focuses on the Microwave range of the EM spectrum. With the advent of smart technologies, Microwave has reached each house and every individual, which makes precise and traceable electromagnetic measurements and hazardless interconnectivity very important. CSIR-NPL (NMI of the country) provides measurements for microwave frequencies from 9 kHz to 110 GHz frequency range that are precise, accurate, reliable, internationally recognized and traceable to the SI units through Microwave Metrology. The Microwave based National Standards and measurement capabilities are realized, established,
maintained, and upgraded at CSIR-NPL. These standards are disseminated to reference laboratories across India to provide traceability to various sectors: strategic, defence, manufacturers, testing industries, government regulators and research institutions. Microwave metrology at CSIR-NPL has a unique combination of comprehensive capabilities of various parameters of Electromagnetics such as attenuation, microwave power, E-Field and specific absorption rate (SAR), along with various free space measurements parameters. Upcoming 5G technology is not just a routine technological change but a platform to enable several smart technologies such as smart banking, smart city, smart village, smart healthcare smart automobile and many more. This shows the overall impact of Microwave metrology on country’s upcoming technological needs. Based on impact analysis of dissemination of microwave metrology by the NMI of India, its role on technological revolution will be discussed in detail. This chapter comprises of closed system microwave parameters such as attenuation, impedance, insertion loss followed by free space microwave measurements such as Electric Filed, SAR, Shielding effectiveness, dielectric measurements along with advanced Quantum E-Field measurements traceable to Plank Constant. Each parameter is discussed in terms of its associated primary standards, their calibration and measurement capabilities (CMCs) and their degree of equivalence with the leading NMIs of the world, and on-going research for advanced measurements including quantum standards. Next section of all microwave metrology parameters deals with their impact on quality infrastructure creation at strategic, defence and industrial fronts. How ministries, regulators, manufacturers, industries, academia and research institution directly/indirectly benefit from these parameters in terms of calibration, testing, training, human resource development and technical consultancy is discussed in detail. Questions related to the issues such as—the measurement challenges, effect on industrial certification and technical consultation, challenges for regulators to catch up with upcoming series of modified standards—associated with the advent of technology in electromagnetic domain are dealt with. The importance of a strong link amongst the ministries, regulators, NMI (CSIR-NPL) and industries evolving as a game changer to enhance export and improve the quality of import will be discussed. The impact of electromagnetic metrology on overall economic growth of the country and ‘Aatmanirbhar Bharat’ are outlined.

One accurate measurement is worth a thousand expert opinions.

— Grace Hopper (1906-1992)
11.1 Introduction

‘Electromagnetic’ spectrum is a term used for referring to electromagnetic radiation, for frequency range from $1$ to $10^{20}$ Hz, which can further be classified into two parts, non-ionizing (1 Km to 100 nm) and ionizing (100 nm and up to 1 Å) [1], based on the energy EM wave carry at a particular frequency. Electromagnetic metrology at CSIR-NPL has calibration and measurement capabilities for $1 \text{ Hz}–10^{11}$ Hz of electromagnetic spectrum. These calibration and measurement capabilities cater to almost all sectors of electrical and electronics industries as well as other interdisciplinary industries such as the automobile sector, biomedical devices, industrial RF heating instrumentation, and many more. Electromagnetic metrological services at apex level in the country cover parts of EM spectrum having day to day interaction in human life. The non-ionizing EM spectrum (1 Hz–110 GHz) covers area of services from household appliances to advance communication system, defence to strategic sector, electrical and electronics to automobile industry, aviation to naval dockyard, advance material characterization to biological liquids and magnetic fields to electric field generation and measurement as per their broad applications. The influence of EM metrology can be ascertained from the huge economic impact it can have on various industries it caters to.

Electrical and electronic industry has shown an optimistic growth since 2014, but the deficit between import and export has side lined the serious efforts made by regulators and manufacturers under ‘Make in India’ initiative [2]. As per available reports [3, 4, 5] in the public domain, the total electronic manufacturing in India has grown by a minimum of threefold since 2014. A figurative comparison of electronics export between India and China as shown in Fig. 11.1 explains the export growth scenario very clearly. Indian export reached up to 90 billion INR in 2019, almost double that of 2018 [6].

![Graph of India vs China Exports](image)

**Fig. 11.1** Export comparison between India and China (Y-axis is in INR Billion) [6]
Similarly, as per Indian Electrical and Electronics Manufacturers’ Association (IEEMA), the apex Indian industry association of manufacturers of electrical, industrial electronics and allied equipment concluded, based on their compiled data, that the electrical and electronics industry has witnessed a record double-digit growth of 12.8% in 2017–18 [7]. Potential growth associated with electric and electronics industry based on home appliances is still very bright. As per the latest reports [8], the five primary categories in the appliances and consumer electronics market—ACs, TVs, audio, refrigerators, and washing machines - is projected to have a compounded growth rate of 11.7% between 2018/19 and 2024/25. Similar situation will be present in almost every sector of electrical and electronics post Covid-19 new normal and ‘Aatmanirbhar Bharat’ [9] framework.

The third industrial revolution was about connecting each and every device with internet to control them via remote access and fourth industrial revolution is about converting a technology to smart technology; and it will be driven by IoT based interconnectivity from smart household electrical appliances to smart automobiles, smart offices to smart biomedical assistance and will be available on individual’s fingertip via a smart phone. This fourth generation of industry will be derived from very sensitive smart sensors based on low voltage/current or magnetic field and their interconnectivity with IoT based smart phones, new upcoming devices via smart communication devices connected to smart base station, which will get power from a smart grid within assigned exposure EM limits. The interconnectivity of these devices with decision making capabilities to sustain the ecosystem with minimum interference to coexisted devices will be the key challenge in upcoming time and will be discussed in detail in following sections.

The true potential of the electrical and electronics sector can be reaped only via a sound and efficient quality infrastructure in India, which is reflected in the policies of the Indian government. The government of India launched National Policy on Electronics 2019 (NPE 2019 [10]) on 19 February 2019 with a target of $400 billion in domestic electronics manufacturing by 2025, of which $190 billion is expected to be contributed by exports with one crore job opportunities. One key target of this policy is to boost mobile manufacturing to one billion units, with exports targeted up to 0.6 billion units. Similarly, a committee by the honourable prime minister to make India an electronic manufacturing and export hub in the world, chaired by NITI Aayog CEO with several international members and world-leading manufacturers has been setup to come up with suggestions [11] to reduce India’s ‘disability’ to export or high production costs. Key recommendations of this committee as well as NPE 2019 are very similar and explain the importance of quality infrastructure in the country. Following are the points of concern, as per committee’s recommendations:

(a) Cost-effective solution
(b) Quality Assurance of the product
(c) Certification as per the world’s advance standardization to enhance export in Europe and USA
(d) Robustness of the products
(e) Certification without any trade barrier.
Electromagnetic Metrology addresses the suggestions of the NPE 2019 to boost the export by providing framework to ensure quality infrastructure and support industries by enabling testing and certification domestically at par with international standards to match export level quality. EM Metrology at CSIR–NPL can be further categorized into major metrology parameters based on EM frequency and their applications: starting from microwave metrology followed by LF and HF voltage, current and PMU metrology, magnetic metrology, quantum voltage metrology and FIB application for metrology. In the present Part-I of the chapter, we discuss the microwave metrology in detail. The next Part-II of the chapter will discuss remaining significant parts of Electromagnetic Metrology covering the details of LF and HF voltage, current and PMU metrology, magnetic metrology, quantum voltage metrology and FIB application for metrology.

Microwave Metrology at CSIR-NPL [12] exhibits an international degree of equivalence for various measurement parameters such as Microwave Power, Attenuation, Impedance, E-Field, Shielding Effectiveness, Radiated power density, Specific Absorption Rate in the frequency range from 9 kHz to 50 GHz with fifteen registered CMC’s and seven international inter-comparisons. Indigenized instrumentation is the crucial aspect of this parameter, where primary standards for Attenuation, E-Field, SAR and shielding effectiveness have been developed in-house. With upcoming facilities such as EMI/EMC, IoT/Vector SAR and Rydberg Atom based measurement and Quantum Communication, the metrology capabilities will extend to almost all advanced electronics manufacturing sectors supporting Defense, DGCA, MEITY, MoCA and DoT with TEC. The total impact of only the telecom industry is estimated to be a minimum 8.2% of India’s GDP. A detailed discussion about the above points will be followed in the respective section.

From the discussion above, it is self-explanatory that the Microwave metrology can support various national missions such as Make in India, Electric Vehicle Policy 2019, NEP 2019, National Digital Communications Policy-2018 and National Mission on Quantum Technologies and Applications (NM-QTA) by establishing a quality infrastructure in the country that can provide all technological solution to the measurement requirement from these various sectors. The chapter further explains each parameter associated with Microwave Metrology in detail including the associated primary standards, their calibration and measurement capabilities with the international status. Also, the role of the Microwave metrology in quality infrastructure with identified sectors, regulators and ministries along with the economic impact analysis is also provided.

### 11.2 Microwave Metrology

Microwave Metrology at CSIR-NPL provides apex level calibration services in microwave attenuation, impedance and E-field strength parameters to the industry and user organizations of the country. In order to meet the growing demand for calibration of new age wireless devices in this era of continuously growing technology,
the focused research and development activities at CSIR-NPL towards the microwave metrology also grows continuously and can be classified into three main domains of Microwave Engineering:

- Instrumentation and measurements (antenna measurement, attenuation and impedance measurement up to 40 GHz, E-field standards, Radiated power density standards, SAR measurement, dosimetric E-field and SAR probes)
- Analytical modelling and design (microstrip antenna, material characterization in microwave, computational modeling of SAR)
- Research towards Quantum Standards for direct SI traceability against universal constants.

CSIR-NPL (NMI of India) disseminates the traceability from various range of parameters ranging including microwave power, attenuation, impedance up to 40 GHz, along with measurements for E-Field strength and radiated power density up to 6 GHz and several other derived parameters and measurement capabilities which will be discussed in detail in following sections.

11.3 Measurement Capabilities and SI Traceability

This section outlines the measurement capabilities and their traceability to SI Units has been discussed in detail. Each parameter has been elaborated with their scientific basis and their application in measurements.

11.3.1 Primary Standards

Primary standards associated with microwave metrology, both of derived units as well as of independent parameters is discussed in following section.

11.3.1.1 Power Measurement

A 2.4 mm coaxial microcalorimeter system based on thermoelectric principle has been realized as the national standard of microwave power at CSIR-NPL [13]. The design is based on two symmetrical and thermally isolated transmission lines, one connected to power standard and the other connected to an identical power standard used as a thermal reference. This complete system is immersed in water for thermal stability as shown in water vat section in Fig. 11.2. The submerged system is illustrated mathematically in Fig. 11.3. The main function of the system is to determine the temperature variation between the two power standards, which is of the order of few milli-Kelvin, using a specially designed thermopile. The coaxial microcalorimeter along with the thermocouple power sensor will provide traceable measurements from 1 MHz to 50 GHz.
Fig. 11.2  Block diagram of the complete calibration system

Fig. 11.3  Mathematical model for evaluation of effective efficiency
i. **Efficiency**
   The efficiency is obtained from the first reference measurement in low frequency (200 Hz). Alternatively, the LF signal and the RF signal, at the calibration frequency, is injected in the thermopile. The level of the RF signal is adjusted to obtain a sensor thermocouple output voltage similar to the one obtained with the LF signal. Where, $e_{LF}$ and $e_{RF}$ are the microcalorimeter thermopile output voltages and, $V_{LF}$ and $V_{RF}$ are the microcalorimeter sensor output voltages, when the LF and RF signals are applied respectively. The efficiency uncertainty ($k = 1$) is obtained from mentioned in Fig. 11.3.

ii. **Effective Efficiency**
   The effective efficiency is obtained from both the efficiency and the thermal isolation coaxial line attenuation ($A(dB)$) using the expression shown in Fig. 11.3.

iii. **Measurement results**
   An interlaboratory measurement comparison of microwave power for the validation of the 2.4 mm coaxial microcalorimeter system has been carried out between CSIR-NPL and Laboratoire National de Métrologie et d’Essais (LNE) France. The difference between the effective efficiency evaluated by the two laboratories was less than 0.5% at all frequency points, as shown in Fig. 11.4.

![Effective Efficiency Comparison](image-url)

*Fig. 11.4  Effective efficiency measurement comparison*
The normalized error value of CSIR-NPL for effective efficiency varies between $-0.23$ and $+0.09$ with respect to LNE. The result shows good agreement in assigning the effective efficiency to power sensor among the two labs within their claimed expanded uncertainty. It proves the degree of equivalence in measurements between two national metrology institutes (NMIs).

The absolute value of the effective efficiency has been assigned to the microwave power standard from 1 MHz to 50 GHz using coaxial microcalorimeter and Vector network analyzer. The expanded uncertainty at 50 GHz is $\pm 1.9\%$. The system has been validated with the measurement results of LNE France (Fig. 11.4). The maximum difference observed is 0.0042 between the values of LNE France and CSIR-NPL at 45 GHz. The effective efficiency assigned lies within the uncertainty of both the NMIs.

iv. **Traceability Chart of Microwave Power Measurement**

The traceability chart for microwave power measurement is a bit complex, as it relies on SI unit from dimensional metrology and impedance metrology driven from Josephson Voltage Junction and Quantum Hall Resistance again a SI traceable system (shown in Fig. 11.5). From the chart it is obvious to say that the sources of error will increase with each level down the traceability chart and at the end it reaches to microwave power sensor, the most common diode base device to measure microwave power since 1970.

### 11.3.1.2 Attenuation Measurement

Attenuation can be understood as the insertion loss generated when a device is inserted in between a perfectly matched the generator and load. It is measured in two steps. First, the power is measured when only impedance matched source is connected to the power sensor and this value is taken as reference. Second, a Device Under Test (DUT) is placed in between the source and power sensor and power received is recorded. The difference between the recorded value from the reference value is the attenuation of the DUT. The power from the sensor is measured by a power meter. Attenuation is thus given as:

$$A(dB) = 10 \log_{10} \left( \frac{P_1}{P_2} \right) \quad (11.1)$$

where, $P_1$ is the power indication without the attenuator in line, and $P_2$ is the power indication with the attenuator in line.

A dimensional artefact based 30 MHz Waveguide below Cut-Off (WBCO) attenuator is the first primary standard of attenuation at CSIR-NPL, with uncertainty of $\pm [0.004 + 0.0001 \times \Delta \text{A}]$ for a range up to 60 dB [14]. The WBCO is a hollow tube of brass (perfectly conducting cylinder) which acts as a waveguide below cut-off transmission line at 30 MHz, which allows propagation of only resonant mode (TE11) with the help of mode filter. The basic illustration of the WBCO is given in Fig. 11.6,
Fig. 11.5 Microwave power measurement traceability chart

Fig. 11.6 Inner Schematic of WBCO attenuator

...which explains the role of distance between two inductive coils to generate a fixed value of attenuation at a certain distance followed by the role of grid to propagate dominant mode only.
For perfectly conducting cylinder walls with a coil separation $d_1$ to $d_2$, the attenuation in dB may be found from following expression in terms of dominant mode $S_{mn}$ and wavelength $\lambda$,

$$
\alpha_p = 8.8682\pi (d_1 - d_2) \left[ \left( \frac{S_{mn}}{2\pi r} \right)^2 - \left( \frac{1}{\lambda^2} \right) \right]^{0.5}
$$

(11.2)

Before 2012, this facility was traceable to NMI Australia, now with the help of IF substitution technique this measurement is traceable to inductive voltage divider at 1 kHz IF frequency.

i. **IF Substitution Technique**

Intermediate Frequency (IF) substitution technique measures the attenuation at various frequencies with the help of mixers, as shown in Fig. 11.7. In the IF substitution technique, the system compares the attenuation through the device under calibration with an IF attenuation standard. A mixer along with an IF receiver is introduced into the measurement system to generate the desired IF frequency. To perform this substitution method, two different RF sources are used. A mixer with calculated non-linearity is deployed between the RF source and Local oscillator. The mixer is a three-port device, the two RF sources act as an input to the mixer, and the difference between their frequencies will generate an intermediate frequency on the output port. In the measurement, 30-MHz substitution technique is deployed because of the 30-MHz tuned receiver (VM7), shown in Fig. 11.7. Here, VM7 is a 30-MHz tuned receiver with the in-built local oscillator [15].

In the last 5 years, the microwave attenuation and impedance measurement systems are completely automated at microwave metrology at CSIR-NPL. An attenuation measurement system, which employs a traceable Inductive Voltage Divider (IVD) at 10 kHz as the reference standard and dual-channel Intermediate frequency (IF) substitution method, is developed as the attenuation standard to calibrate the 30 MHz WBCO in the frequency range 30 MHz–18 GHz with an uncertainty of ±0.005 dB/10 dB. This measurement method requires a precise

![Fig. 11.7 Schematic diagram of 30 MHz IF substitution technique](image-url)
mixer which can down convert the 30 MHz signal to 10 kHz signal for the IF substitution. A mixer was designed and indigenously made at CSIR-NPL, which can down convert 30 MHz signal to 10 kHz signal. The linearity of the designed mixer at different power levels is shown in Fig. 11.8, which is within the $\pm 0.006$ dB range.

The calibration of WBCO using the dual channel IF substitution technique was carried out at CSIR-NPL and the recorded values are compared with the values reported in earlier certificate of WBCO calibrated by NMI Australia. The measured values from both the measurement techniques are in degree of equivalence and are shown in Fig. 11.9.

In the past few years, fully automated in-house calibration of the primary standard is established based on inductive voltage divider (IVD) based technique. Microwave Metrology provides apex level calibration services for attenuation from 0.05 to 90 dB at 30 MHz and 1 to 50 GHz with an uncertainty of $\pm 0.005$ dB/10 dB.

ii. Traceability Chart for Attenuation Measurements

![Traceability Chart for Attenuation Measurements](image-url)
As explained earlier, the attenuation parameters at microwave metrology was traceable to NMI Australia via calibration of WBCO against their primary standard. But, now the WBCO calibration facility was established in house against the registered CMC of 1 kHz IF substitution measurement with the help of IVD (Fig. 11.10). Further dissemination of attenuation parameters is being carried out with the help of VM7 receivers and commercially available attenuators.

### 11.3.1.3 Scattering (S) Parameters Based Impedance Measurements

Scattering parameters define the forward and reverse wave propagation through a network. Abundant literature [15] is available on the theoretical elucidation of S-parameters. A brief description here will help in understanding the basic concept of S-parameter and its measurement. Considering the example of a two-port network, shown in Fig. 11.11, S-parameters define the relation between the input and outputs from the network. In general, the S-parameters for a two-port network can be given as:

![Fig. 11.11 Two-port device in terms of S-parameters](image)
\[ b_1 = S_{11}a_1 + S_{12}a_2, \quad (11.3) \]
\[ b_2 = S_{21}a_1 + S_{22}a_2, \quad (11.4) \]

where, \( a_1 \) and \( a_2 \) are the signals entering the Port 1 and Port 2 of the two-port network and \( b_1 \) and \( b_2 \) are the signals leaving the respective ports.

\( S \)-parameters can be generalised for any \( n \)-port device and all network properties can be expressed in terms of its \( S \)-parameters. Now a days, sophisticated network analysers are available, which can directly give the \( S \)-parameters (and other network properties) of a device connected to its port(s). For characterizing a two-port network for impedance using its \( S \)-parameters, a VNA comprising of a RF source, bridges/couplers, mixers and tuned receiver is required in order to measure the forward and reverse signals at both the ports.

i. Vector Network Analyzer (VNA):

Vector Network Analyzer is a device which measures different network parameters of electrical networks based on transmission and reflection of EM waves in transmission line. It consists of a set of source and receivers; the source generates signals which pass through the device under test and routes it to receivers which analyse the received signal and decides the losses occurred due to the DUT. In general practice, a VNA is calibrated by the common techniques such as SOLT, TRL, multiple short and broadband, etc.[16].

CSIR-NPL being NMI of India cannot apply these common methods of VNA calibration, as the dimensions and other properties of these co-axial devices may change or degrade with time. Coaxial Air-lines with air in between their inner and outer conductors are used as primary standard for VNA calibration at CSIR-NPL [17]. The VNA calibration consists of a calibration of diameters of inner and outer connectors of all co-axial devices from dimension metrology and impedance calibration from DC resistance metrology, this process is represented in the traceability chart.

In the measurements through VNA there are multiple sources of errors and uncertainties, which need to be evaluated carefully. A plane or reference is to be identified in which the electrical length plays the major role to identified several uncertainty sources such as Directivity, Source match, Reflection tracking, Transmission tracking and load match, Isolation, Drift, Test port cables, Non-linearity, and Repeatability based on ten term error model [16] or ripple method [17]. Our clients such as ERTL, ISRO, IAF get their co-axial devices and calibration kits such as open, short, load, broadband etc. calibrated against our primary standard. The calibration of these devices is done using standard techniques mentioned above.

ii. \( S \)-parameter Measurement

The key comparison named \( SIM.EM.RF-K5b.CL \) [18] was held between NMIs of the world for \( S_{21} \) measurement of a 3 dB attenuator at 9 GHz. CSIR-NPL had participated
in this and the measurement data reported on BIPM website is shown below in Fig. 11.12. The measurements were in degree of equivalence with the world leading NMIs. Similarly, other key comparisons have also been participated in and their results are reported in CMC section below.

iii. **Traceability Chart for Impedance Measurement**

Traceability of impedance standard (Fig. 11.13) is derived from dimensional metrology (for meter \((m)\)) and quantum Hall resistance \((\Omega)\). Electrical length of airline and resistive and reactive values from Hall resistance are used to derive the

---

**Fig. 11.12**  \(S_{21}\)
Measurement results of key comparison SIM.EM.RF-K5b.CL [18]
polynomial of resistance, capacitance and inductance. These polynomials are then used to evaluate the cal-kit parameters calibrated at CSIR-NPL for various organizations. These cal-kits are then used to calibrate various instruments and thus provide traceability to the measurements by respective organizations. Thus, the chain of traceability is established.

11.3.1.4 Electric-Field Strength and Radiated Power Density Measurement

E-Field strength is the essential parameter for all free space measurements in RF frequency. It can be used to derive several parameters such as radiated power density, antenna factor, antenna gain, radiation pattern and intensity for antenna, shielding effectiveness, free space measurement and SAR. Microwave metrology at CSIR-NPL has established the in-house calibration facility for the E-field strength generation and measurement based on completely indigenous instrumentation. The E-field strength standard at CSIR-NPL relies on measurements performed by DUT probes inside the TEM cell, where uniform E-field is created by a RF source. One may refer to [19] for further insight into the measurement setup and procedure.

The Transverse/Gigahertz-Transverse Electromagnetic Cell (TEM/GTEM cell), as shown in Fig. 11.14, can be used to test the minuscule RF devices such as mobile phones, integrated circuits, PCBs, micro-electromechanical systems, and also the E-field probes. A thorough analysis of all the important parameters that affect the working of a TEM cell had been carried out while designing the cell at CSIR-NPL. The complete precise measurement methodology adopted for an isotropic probe [19] is now used as the calibration procedure for Electric Field strength measurement parameter. IEEE Std. 1309–2013 is consistently followed for calibration of E-field probes, which then can be used to measure the radiated power density from the different devices and cellular towers.

The uncertainty in E-field strength measurement is $\pm 0.58$ V/m per 10 V/m for different frequency in the range from 700 MHz to 3 GHz. Indigenous E-field probes are also designed and fabricated in-house, which are technically competent with the commercially available probes. E-field strength parameter in the microwave range is

Fig. 11.14 Schematic diagram of a basic TEM cell b probe calibration inside TEM cell [20]
**Fig. 11.15** Cross sectional view of TEM cell

of great importance for the compliance testing of wireless communication devices and has great socio-economic impact.

The schematic diagram of TEM is shown in Fig. 11.14 with a cross-sectional view in Fig. 11.15, where the Electric Field inside TEM depends on the separation between the plates (conductors) and area of the plates i.e., the width and the length of the plates. The characteristic impedance inside the GTEM based on between plate capacitance and fringing capacitance can be defined as [19]:

\[ Z_0(\Omega) \approx \frac{94.15}{(\varepsilon)^{1/2} \left(\frac{w_T}{L_T(1-r/L_T)} + \frac{C_f'}{0.0885\varepsilon_r}\right)} \]  \hspace{1cm} (11.5)

where, \(C_f'\) is the fringing capacitance in pF/cm, \(\varepsilon_r\) is relative dielectric constant, \(r\), \(L_T\) and \(W_T\) are shown in Fig. 11.15.

Other expressions that are useful for characterizing a TEM cell are Cell resonant frequency,

\[ f_{res} = \sqrt{f_c^2 + \frac{(\varepsilon)^2}{2l}} \]  \hspace{1cm} (11.6)

where \(f_c\) is the cell cut off frequency and \(l\) is the resonant length of the cell.

and Cut off frequency,

\[ f_c = \frac{75}{a} \sqrt{\frac{2aL_T}{d_1d_2\ln\left(\frac{8a}{\pi g}\right)}} \]  \hspace{1cm} (11.7)

where, \(g\) is the distance between the side walls of the cell and the septum.

Theoretically, the generated E-field strength measured by an ideal isotropic probe inside the TEM cell is calculable and given by Eq. 11.8:
where, $P$ is the input power to the cell, $Z_r$ is the real part of the characteristic impedance and $a$ is the vertical distance between the septum and the inside wall of the cell. The performance of designed TEM is reported in Fig. 11.16.

### i. Design, fabrication and characterization of E-field sensors

For characterizing the microstrip antenna as an E-field probe, its gain, antenna Factor ($AF$) and E-field strength are measured and compared with a calibrated isotropic E-field probe. A novel way of using $AF$ to evaluate the accuracy of E-field measurement is eventually devised. It is realized that accuracy of such probes needs to be studied in terms of return loss, $AF$, probe linearity and mismatch. When an antenna is used as an E-field probe, it becomes advisable to evaluate the $AF$ of the antenna, which can be used as a multiplying factor for evaluating the E-field strength from the measured voltage at the probe. The antenna factor is given by [20],

$$AF = 20 \log_{10} \left( \frac{E_i}{V} \right)$$ (11.9)

where, $E_i$ is the incident E-field and $V$ is the received voltage.
For the wave propagating in free space, the E-field is related to radiated power density $S$ (in W/m$^2$) and the intrinsic impedance $\eta$ of free space (in ohms) as

$$|E_i| = \sqrt{\eta S}.$$  \hspace{1cm} (11.10)

Also, the received power $P_r$ is dependent on received voltage $V$ and load impedance $Z_{\text{load}}$ as

$$P_r = S \times A_e = \frac{V^2}{Z_{\text{load}}},$$  \hspace{1cm} (11.11)

where, $A_e$ is the effective aperture dependent on the operating wavelength $\lambda$ and gain $G$

$$A_e = \frac{\lambda^2 G}{4\pi}.$$  \hspace{1cm} (11.12)

E-field strength 9.99 V/m at 915 MHz with an expanded uncertainty of $\pm 0.58$ V/m at fed power $+18$ dBm has been reported for the TEM cell fabricated at CSIR-NPL [19].

A comparative study has been performed for various E-field measurement standards of several NMI’s based on literature and presented in Table 11.1 below. The reported values of radiated power density, calibration method and the associated uncertainties are reported in the Table 11.1.

Data in Table 11.1 are sourced from inter-comparison EURAMET.EM.RF-S25 [21] for 10 V measurements and CCEM.RF-K7.a.F.2 [22] for minimum sensitivity level. CSIR-NPL did not participate in any of these intercomparison and the data are compiled to outlay the degree of equivalence of its measurement capabilities.

### ii. Traceability Chart for E-field Measurement

| Country | NMIs         | Calibration method               | Uncertainty in E-field strength* (V/m) | Radiated power density limit |
|---------|--------------|----------------------------------|--------------------------------------|-----------------------------|
| UK      | NPL UK       | TEM cell and Tapered GTEM Cell    | $\pm 0.35$                           | 100 $\mu$W/m$^2$            |
| France  | LNE, France  | GTEM Cell                        | $\pm 0.60$                           | 1mW/m$^2$                   |
| Germany | PTB, Germany | Micro TEM Cell                   | $\pm 0.69$                           | 2mW/m$^2$                   |
| Korea   | KRISS, Korea | Micro TEM Cell                   | $\pm 0.70$                           | 2mW/m$^2$                   |
| USA     | NIST, USA    | Micro TEM Cell                   | $\pm 0.45$                           | 500 $\mu$W/m$^2$            |
| India   | NPL, India   | Micro TEM Cell                   | $\pm 0.60$                           | 1mW/m$^2$                   |
CSIR-NPL is in the process to register its E-Field strength measurement capability as a CMC at BIPM and this measurement has yet not been registered. A detailed traceability chart is given in Fig. 11.17, explaining degree of equivalence in the E-Field measurements being ensured with world leading NMI through participation in various international inter-comparisons on other key parameters and other traceable standards.

![Traceability Chart of E-Field Measurement](image)

**Fig. 11.17** Traceability chart for E-field measurement
11.3.1.5 Specific Absorption Rate

Specific absorption rate (SAR) is the measure of the heating value of radiated RF energy on a body or material such as human tissue. The absorption of electromagnetic (EM) wave is mainly due to the dissipation of its energy, i.e., conversion of its energy into another form, such as heat. The rate at which any material absorbs the incident EM wave is generally expressed in terms of SAR. It is one of the most fundamental dosimetric parameters used by various telecommunication regulatory bodies for specifying the maximum limits of exposures to minimize the adverse effects of the smart wireless devices on humans.

Specific absorption rate value, given in terms of Watt/kg can be defined as the rate of absorption of RF power in a material,

\[
SAR = \frac{\sigma(\omega)|E|^2}{\rho},
\]  

(11.13)

where, \(\sigma\) is the conductivity of the material (S/m), \(E\) is the Electric field strength (V/m) and \(\rho\) is the mass density of the material (kg/m\(^3\)).

Another definition of SAR is given in terms of rate of increase of temperature in a material, given by,

\[
SAR = \frac{c\Delta T}{\Delta t} \bigg|_{t=0},
\]

(11.14)

where, \(c\) is the specific heat capacity (J/kg °C), \(\Delta T\) is the change in temperature (°C) and \(\Delta t\) is the duration of exposure (s). For this measurement, “ideal” non-thermodynamic circumstances are made i.e. no heat loss by thermal diffusion or heat radiation. The typical SAR measurement setup is schematically shown in Fig. 11.18a.

Fig. 11.18  a SAR Measurement setup schematic and b Actual photograph of SAR measurement setup at CSIR-national physical laboratory
A Specific Absorption Rate (SAR) evaluation system is indigenously developed by CSIR-NPL (Fig. 11.18b). In this setup E-Field Sensor probe, Tissue equivalent liquid, Robotic arm (EPSON C8-A701S) and a controlled GUI are being indigenously developed [23]. The system is capable to evaluate SAR up to 3 W/kg with an expanded uncertainty of ±0.25 W/kg per 1.6 W/kg.

As per Eq. 11.13, it is obvious that SAR measurement is derived from E-Field measurement and conductivity of tissue or tissue equivalent liquids. The conductivity tissues/TEL is defined at a particular frequency as per IEEE 1528–2013 standard and can be calculated from imaginary part of S-parameters. Hence, traceability of SAR measurement is combination of two traceability charts: one E-Field and second impedance. Same is reflected in Fig. 11.18. Till date, no inter-comparison for SAR measurement standard has been carried out or yet proposed, as per KCDB [24] database. But for establishing the degree of equivalence in measurement, CSIR-NPL has now become a part or EURAMET consortium on project SAR measurement using vector probes (Project Number: 16NRM07) so that traceability for any upcoming standards can be obtained in future for Mobile and wireless compliance for Indian Telecom industry. It will also provide the technical capability to address 4th industrial revolution as per smart and wearable wireless devices are concerned.

11.3.2 Calibration and Measurement Capabilities (CMC)

11.3.2.1 CMC at BIPM

To register CMC of any parameter at BIPM [24], an activity of NMI should have primary calibration system with minimum degree of freedom to have minimum uncertainty contributions. The associated sources of uncertainties of that parameter should be identified and properly evaluated against various measurements. A validation method is also essential to evaluate the claims of the primary standard. After having all these facilities, an NMI can participate in inter-comparison for the calibration and measurement capabilities. If the measurement results are well within degree of equivalence, then the activity is reviewed by a peer appointed by RMO and later gets accepted by chairman of technical committee at BIPM and finally CMC gets registered at BIPM website. The parameters for which CSIR-NPL has CMC registered at BIPM are given in Table 11.2.

11.3.2.2 List of Measurement Capabilities

This section includes the list of the other parameters for which CSIR-NPL can measure and calibrate with calibration procedure with uncertainty budget as per established methods but not yet peer reviewed and approved by BIPM.

As a result of continuous research in the field of RF and microwave metrology CSIR-NPL has upgraded all existing measurement and calibration facilities to the
values reported in Table 11.3 for various parameters. Uncertainty budget for all the parameters have been made and are reported to APMPGA 2017 for CMC registration.

### 11.3.2.3 List of Inter-Comparison

Microwave metrology at CSIR-NPL keeps participating in inter-comparisons from time to time to upgrade our existing measurement capabilities add new measurement capabilities. Some of the inter-comparisons are listed in Table 11.4.

From above table of intercomparison it is obvious to say that microwave metrology is committed to have a degree of equivalence with leading NMI such as NIST- USA, PTB-Germany, NPL- UK, NRC-Canada, and AIST-Japan on almost all measurement capabilities so that Indian manufactured product could have a free trade as per all technical certification requirements. Some degree of equivalence in measurement with above listed NMI’s is given below for reference from [18, 28].
| TAG | Quantity | Instrument or artefact | Measurement method | Parameters |
|-----|----------|------------------------|--------------------|------------|
| 1   | Radio frequency power: absolute power in coaxials | Power meter, power source | Direct measurement or comparison | Frequency: 1 MHz–18 GHz, Connector: N, APC-7 |
| 2   | Radio frequency power: calibration factor and efficiency in coaxials | Thermistor, barretter mount and power sensor | Direct comparison | Frequency: 10 MHz–18 GHz, Connectors: N, APC-7 |
| 3   | Scalar RF reflection coefficient and attenuation: VSWR in coaxials | Passive device: matched termination and standard mismatch | Coupled sliding load technique | Frequency: 2 GHz–18 GHz |
| 4   | Scalar RF reflection coefficient and attenuation: reflection coefficient in waveguides | Passive device: matched termination and standard mismatch | Tuned reflectometer technique | Frequency: 5.8 GHz–18 GHz (spot frequency) |
| 5   | Scalar RF reflection coefficient and attenuation: attenuation in coaxials | Passive device: fixed/variable attenuator/attenuator and signal calibrator | Substitution technique | Frequency: 30 MHz |
| 6   | Scalar RF reflection coefficient and attenuation: attenuation in coaxials | Passive device: fixed/variable attenuator | IF substitution technique | Frequency: 1 GHz–18 GHz |
| 7   | Radio frequency voltage and current: RF-DC difference | RF micro-potentiometers | Comparison | Frequency: 1 MHz–1 GHz |
| 8   | Radio frequency voltage and current: RF-DC difference | Thermal voltage converter | Comparison | Frequency: 1 MHz–1 GHz, Impedance: 50 Ω |

(continued)
### Table 11.2 (continued)

| TAG | Quantity | Instrument or artefact | Measurement method | Parameters |
|-----|----------|------------------------|--------------------|------------|
| 9   | Radio frequency voltage and current: RF voltage sources | RF generator | Comparison | Frequency: 1 MHz–1 GHz, Impedance: 50 Ω |
| 10  | Radio frequency voltage and current: RF voltage meters | RF voltage meter | Comparison | Frequency: 1 MHz–1 GHz |
| 11  | Scalar RF reflection coefficient and attenuation: attenuation in waveguides | Passive device: fixed/variable attenuator | Intermediate frequency substitution technique | Attenuation [0.1–60] dB, Frequency: 1 MHz–40 GHz |

### Table 11.3  List of parameters CSIR-NPL is capable of measuring for the range reported against the respective parameter

| Parameter | Range | System | Uncertainty |
|-----------|-------|--------|-------------|
| Attenuation | 0.005–107 dB | 30 MHz Coaxial system | ±0.007 dB/10 dB |
|           | 0.005–90 dB | 9 kHz–40 GHz Coaxial system | ±0.02 dB/10 dB |
|           |          | 5.85–40 GHz Waveguide system | ±0.02 dB/10 dB |
| Reflection coefficient/VSWR | 1.02–5 | 9 kHz–50 GHz Coaxial system | ±0.02 in VSWR ±0.002–±0.003 in |\(|\Gamma|\) |
|           | 0.01–0.2 | 5.85–40 GHz Waveguide system | ±0.02 in VSWR ±0.002–±0.003 in |\(|\Gamma|\) |
| Phase | −180°–180° Phase | 9 kHz–50 GHz in coaxial system | ±0.2° Phase |
|        | 0°–180° Phase | 5.85–40 GHz Waveguide system | ±0.2° Phase |
| E-field (V/m) | 1 µV/cm–100 V/cm | From 1 Hz–6 GHz | ±0.6 V/M per 10 V/m |
| Shielding effectiveness | 60–10 dB | From 30 MHz–40 GHz in reverberation chamber | ±0.02 dB in 10 dB |
| Dielectric measurement | For Liquid and solid samples | From 8.2 GHz–40 GHz | As per scattering parameters |
| S. No. | Pilot lab     | Type/Identification/ pilot lab       | Parameter/s                                    | Participant countries          | Status                  |
|-------|---------------|--------------------------------------|------------------------------------------------|------------------------------|-------------------------|
| 1     | CSIR-NPL      | Supplementary/P1-APMP.EM.RF-S3/NPL   | Impedance (Complex reflection coefficient)     | KRISS, CMS/ITRI, CSIR-NML     | [26]                    |
| 2     | NPL UK        | Key/CCEM.RF-K5.b.CL/NPL UK           | Complex S-parameters                           | NPL, LNE, NIST, PTB           | [27]                    |
| 3     | NIM China     | Key/APMP.EM.RF-K19.CL/NIM China      | Attenuation                                    | NIMT, NMIA, KRISS, NMIJ       | [28]                    |
| 4     | NMI Argentina | SIM.EM.RF-K5.b.CL/NMI Argentina      | S-parameters by Broad-Band Methods             | KRISS, NIST, CENAM            | [18]                    |
| 5     | CSIR-NPL      | Supplementary/P1-APMP.EM-S8          | DC voltage, current, resistance, AC voltage and current | NIMT, NMIA, NIS, NML-SIRIM    | in process, 2019        |
| 7     | NMI Japan     | APMP.EM.RF-K8.CL                     | APMP Comparison of power in 50 Ω coaxial lines (0.01 to 18 GHz) | NMIJ, KRISS, NIM, NMIA       | in process, 2019        |
| 8     | NMI Japan     | CCEM.RF- K26                        | Attenuation measurements (18, 26.5, and 40 GHz) Max. att. 90 dB | KRISS, LNE, NIM, NPL, PTB    | Draft A 2020            |
| 9     | NMI Japan     | APMP.EM.RF-S5.CL                    | Dimensionally derived characteristic impedance, nominal value: 50 ohms | KRISS, PTB, NIST, LNE, NPL   | Data submitted          |
From Fig. 11.19, it is self-explanatory that microwave metrology represents CSIR-NPL with equivalent measurement capabilities against all leading NMI's. Both two-port coaxial measurement and the one port coaxial measurement at CSIR-NPL have same degree of equivalence with similar order of uncertainties (Fig. 11.20).

### 11.3.3 Derived Measurement Capabilities

#### 11.3.3.1 Missile System Testing

The calibration and testing services for missile guidance system of IAF have been provided by CSIR-NPL, during the crucial time when it was not possible to send the calibration equipment to its manufacturer for testing. The measurements for shielding, transparency and signal strength for the calibration radome and system radome of the missile testing system were performed at CSIR-NPL on various frequency bands.

#### 11.3.3.2 Radiated Power Density Probe Testing for Mobile Tower Radiation Exposure Assessment

RF exposure and safety concerns about usage of mobile and wireless devices have been getting increased attention in recent years. There is continuous media attention and general public concern towards harmful effects of radiations from mobile towers in residential areas. Government has taken this concern into account and specified the exposure limits in line with international regulations. As per revised national telecom policy 2012, the radiation exposure limits are expressed as Tables (11.5 and 11.6).

DoT has laid norms for timely assessment of radiation from mobile towers installed in residential and commercial areas. These assessments are done by various types of probe and meters, which are calibrated by microwave metrology of CSIR-NPL.

This measurement is done by measurement in a closed chamber TEM cell, which produces a uniform field in the range 700 MHz–6 GHz. Standard primary/secondary probe and the DUC probe are placed in the uniform field of particular frequency and measured as shown in Fig. 11.21.

The GTEM cell is fabricated in-house at CSIR-NPL and is calibrated against the primary commercial canonical GTEM cell.

#### 11.3.3.3 Dielectric Measurements for Liquids and Solids:

We provide dielectric assessment for parameters dielectric constant and loss parameters for solid materials like ceramics, sheets, etc. for strategic sectors (CEL,
Fig. 11.20  

a $S_{21}$ Measurement of 3 dB attenuator at 18 GHz  
b $S_{21}$ Measurement of 50 dB attenuator at 18 GHz  
c Reflection coefficient measurement of mismatch (0.01) at 9 GHz
Table 11.5  EMF radiations limits at different frequencies EMF radiations

| Sr. No. | Frequency (MHz) | ICNIRP Radiation limit (W/m²) | Revised DoT norms for radiation limit w.e.f. 01.09.2012 (W/m²) |
|---------|----------------|-------------------------------|---------------------------------------------------------------|
| 1       | 900            | 4.5                           | 0.45                                                          |
| 2       | 1800           | 9.0                           | 0.9                                                           |
| 3       | 2100           | 10.5                          | 1.05                                                          |

Table 11.6  SAR limits at different frequencies EMF radiations

| Sr. No. | Frequency | ICNIRP SAR limits (Watt/kg) | Revised DoT norms for SAR limit w.e.f. 01.09.2012 (Watt/kg) |
|---------|-----------|----------------------------|-------------------------------------------------------------|
| 1       | 10 MHz–10 GHz | 2.0                      | 1.6                                                          |

Fig. 11.21  Radomes calibrated at CSIR-NPL for IAF

Fig. 11.22  Secondary probe measurement for radiated power density in closed GTEM cell
Sahibabad) and manufacturers of various materials. Similarly, measurement for dielectric constant, loss and bulk conductivity of liquid materials such as biological liquids, lossy liquids, etc. are provided for industry and research institutes. Advancements in measurement schemes for these evaluations are also under process (Figs. 11.22 and 11.23).

11.3.3.4 RF Transparency and Shielding Effectiveness for “Covering Sheets” for Strategic Sector Industries

CSIR-NPL has provided Shielding effectiveness measurement for manufacturer of covering sheets for defence personal and vehicles. These are useful for anti-radar and stealth operation (Fig. 11.24). The measurements are done using two port free space method for effective shielding by the sheet for signal of particular frequency in microwave range in X—band and Ku band and K band using horn antennas at a RF noise-controlled room noise floor below −80 dB. Small samples can be tested in the waveguide systems for exact RF transparency with ±3% measurements same can be done in the anechoic chambers for these types of sheets. But to feel real situation
an indoor environment with several reflectors along with working instrumentation, RF sources and multiple reflections is being used on even tilted sheets to evaluate its shielding performance of these sheets in best—and worst-case scenario.

11.3.4 **R&D in Microwave Metrology**

11.3.4.1 **Research for Quantum E-Field Measurement**

Recently, International Bureau of Weights and Measures (BIPM) has decided to redefine all the basic SI units in terms of the physical constants which describe the natural world. This decision, initiated research in all branches of science to make all the derived units traceable to either SI units or to physical constants. The metrological institutes across the world have proved that the atom-based metrological techniques provide more accurate, precise and reproducible results as compared to the conventional techniques. The atom-based standards have been accepted worldwide for measurement of time, frequency, gravity, magnetometry, and length. To date, the RF E-field sensing and calibration techniques does not have traceability to physical constants and have complex traceability path. The dependency on the materials under use, limitation of bandwidth of antennae under use, the surrounding parameters at the time of measurement, and the incorrect evaluation of uncertainties are some of the limitations of current techniques which makes measurable quantity vulnerable to the errors. These measurements will lead to establish the quantum communication and quantum sensing calibration facilities at CSIR–NPL for upcoming smart communication devices.

The technique discussed in this section has many promising benefits over the conventional techniques such as the dependency of dipole antennae (having limited bandwidth of operation) as a reference probe can be replaced by atomic cell which
can sense RF E-fields from few MHz to 500 GHz and beyond. The atoms provide self-calibrating measurements due the invariance in atomic resonances, enhanced sensitivity can be achieved of the order of $1 \mu \text{V m}^{-1}\text{Hz}^{-1/2}$. The field will not be perturbed by the metallic probes as the field is sensed by atomic transitions in this technique.

This technique is based on the interaction of the highly excited alkali atoms with RF energy and utilizes the concepts of quantum interference phenomena like Electromagnetically Induced Transparency (EIT), and Autler-Townes Splitting (ATS). The Rydberg atoms have a huge response to the external E-field which helps in converting the E-field amplitude measurement to the optical-frequency response. The discussed work may find its application in accurate measurement of E-field amplitude which plays a crucial role in the determination of many other parameters such as Specific Absorption Rate (SAR) in biomedical application, EMI/EMC testing of RF and electronic devices, non-invasive RF based detection and diagnostic medical devices, etc.

To measure microwave amplitude via Rydberg atoms a Rb vapor cell is placed as shown in the schematic of the experimental setup in Fig. 11.25a. The counter-propagating linearly co-polarized laser beams interact with the atoms in the presence of microwave (MW) illuminated from the transverse direction to the line of direction of propagation of laser fields by any microwave source with the help of antenna. The weak probe laser of ~780.24 nm tunes the ground state $5S_{1/2} \rightarrow 5P_{3/2}$. Another laser of ~480.044 nm couples the atomic states $5P_{3/2} \rightarrow nD_{5/2}$ (any desired Rydberg state with principal quantum number ‘$n$’) and will be referred to as control laser throughout this section. Both the lasers should be locked so that they should not drift with time. The transmission and absorption of the probe laser is continuously monitored with photodetector. Figure 11.25b shows the atomic ladder model depicting the transitions.

Experimental setup for atom-based E-field sensing is shown in Fig. 11.26. The cylindrical cell placed at top of white platforms act as an antenna. At specific conditions mentioned in [29] the absorption profile of probe beam splits in two peaks giving a transparent window at centre of absorption which is known as EIT. The

![Fig. 11.26](image)

**Fig. 11.26** a Representational setup for the atomic transitions-based E-field metrology; b Energy level structure of the atom
Radio-frequency creates additional interferences resulting in increase in difference between the two split peaks, known as ATS in EIT regime [30]. This behaviour of absorption profile is utilized in RF E-field strength measurement. As the power of incident microwave increases, the split between the two peaks increases which gives us the E-field amplitude by Eq. 11.15:

\[ E_\mu = \frac{2\pi \Delta f}{d_\mu} \hbar \]  

(11.15)

where \( \hbar \) is the Plank’s constant, \( d_\mu \) is the dipole moment of microwave transition, and \( \Delta f \) is the difference between the peaks.

In addition to E-field amplitude measurement, the vector RF E-field determination can also be performed using the same atomic sensor. Rawat et al. [31] have shown that the orientation of microwave E-field vector changes the nature of probe field absorption.

11.3.4.2 Vector SAR Assessment System and Probe Calibration

In the current age of fast evolving communication and being present online virtually always, has made us surrounded by communication equipment everywhere, be it mobile phones, tablet and other wireless devices and the upcoming IoT (Internet of Things) based wearable devices, smart homes, household equipment to smart sensors. We are dependent on these devices for all our day to day work and these are always radiating microwave of other RF radiation. International Standards require that each of these wireless devices to be tested individually, so as to ensure its radiation is within the specified and internationally accepted “safe limit” [32]. For this these
devices need to be tested at each individual frequency on which it operates and for all possible configurations in which the devices may be used. However, this is a tedious and time consuming task to test all these devices, as per existing standard namely IEEE-1528 (2013) [33] and ICNRP guidelines [34]. Also, with continuously upgrading communication technology and increasing number of devices, the task becomes more complex.

Regularity bodies have been working to upgrade these standards and trying to come up with faster assessments methods to accommodate these multiple tests and such large number of devices. Suggested methodology is to make use of time domain probes and arrays which map the amplitude and phase simultaneously and then map the E-field generated by the device. These method uses time-domain Vector probes and MIMO antennas for faster measurements by employing simultaneous amplitude and phase measurements [35]. However, before making these measurements acceptable worldwide the standard for calibration of these probes needs to be established. CSIR-NPL has joined the EURAMET Program 2017 as member in collaboration with LNE, France and other participating NMIs. This program is launched by NPL, UK to address these issues and finally come up with guidelines, procedures and methodologies for SAR assessment using vector probes and their calibration schemes. CSIR-NPL, India has collaborated with coordinator (LNE) to validate their individual measurements and procedures. This collaboration will lead towards comprehensive methods, software tools and datasets required for traceable calibration and uncertainty analysis of vector probe array systems. It will also help incorporate new SAR assessment procedures in the upcoming standards (IEC 62,209–1528/D5 2019 [36] and the latest IEEE Std. C95.1 2019 [37]). These upgradations of existing SAR standards are essential to address the technological change upcoming with smart wireless technologies.

This project aims to address this issue and establish national facility for vector SAR measurement (First of its kind in country) with measurement equivalence to world’s leading NMI for IEC 62,209–3 TC. This will serve as a precise calibration system for the Vector SAR assessment systems proposed. With India emerging as Second largest producer of mobile equipment in recent 2–3 years, there is huge scope to provide SAR assessment to the manufacturers in country itself and save lot of time and cost by having testing at par with new international standards. Microwave Metrology has taken this opportunity and responsibility, being the NMI of India.

11.4 Microwave Metrology for Quality Infrastructure in India

Metrology forms an integral part of Quality Infrastructure which in turns results in High Quality of Life as represented in Well-functioned quadruple helix (QH) [38]. To usher into the phase of ‘Aatmanirbhar Bharat’, i.e., Complete Self-Reliance, we must
utilise of resources sustainably to their maximum potential. The gap in the potential growth and actual growth achieved is often due to weak Quality Infrastructure.

### 11.4.1 Metrological Services for Sectorial Growth

#### 11.4.1.1 Calibration and Testing

Microwave metrology is a promising prospect for private players given the global wireless testing market is expected to grow at a CAGR of 6.7% to USD 14.4 billion by 2024 from USD 10.4 million in 2019. Recent advancements in fields of 4G, 5G, IoT and Smart sensors are pushing the expansion of testing market by adoption of manufacturing techniques that are virtually human intervention-less at the same time maintaining high quality of products [39].

Microwave Metrology offers calibration and testing services for numerous parameters for various types of items spanning across RF attenuation, Reflection coefficient, E-field, and Shielding Effectiveness etc [25]. Special price packages can also be negotiated based on the bulk orders of the customer or based on the custom request from the clients (Table 11.7).

#### 11.4.1.2 Technological and Technical Consultancy

CSIR-NPL can use its expertise in the niche area of metrology in form of guidance and provide consultancy services to various players i.e., Government Bodies, Autonomous Bodies, Research Institutions, Private Industries etc.

- **GTEM with E-Field Sensor Under MPL (Major Lab Project) 160,432**

Radiations from mobile towers, Mobile Phone, Wi-Fi router and Microwave Oven can cause harmful effect on human being which need to be limit as per their radiation is concern. Government of India has made several guidelines regarding maximum radiations from mobile towers and electronic gadgets. To make these measurements traceable in country, CSIR NPL have developed GTEM along with E-Field sensor which is traceable to SI unit. This system will be utilized for the calibration of any E-Field probe or sensor used in wireless communication or Mobile Tower Radiation Measurements. It is a compact, lightweight and small volume system and word wide very few National Metrology Institute has developed this facility. CSIR-NPL India has developed a GTEM cell with E-field sensor based on IEEE Standards 1309–2013. The E-field strength standard is based on Gigahertz Transverse Electromagnetic (TEM) cell. The uncertainty in E-field strength is \pm 0.58 V/m per 10 V/m for different frequency in the range from 300 MHz to 8 GHz. Indigenous E-field probes are also fabricated for Ultrawide band(3–8 GHz), GSM frequencies (700–950 MHz, 1.8–2.45 GHz).
Table 11.7 Various calibration and testing parameters for various Item types at microwave metrology [25]

| S. No | Parameter       | Item name                                | Item type     | Alias name                     | Range                      |
|-------|----------------|------------------------------------------|---------------|--------------------------------|---------------------------|
| 1     | Attenuation    | Coaxial                                 | Attenuator    | Attenuation pad                | 0.1–60 dB                 |
| 2     | Attenuation    | Waveguide fixed attenuator              | Attenuator    | Attenuation pad                | 0.1–60 dB at 5.8–18 GHz   |
| 3     | Attenuation    | Coaxial step attenuator                 | Attenuator    | Variable attenuator            | 0.1–60 dB at 30 MHz and 1–40 GHz |
| 4     | Attenuation    | Rotary vane attenuator                  | Attenuator    | Variable attenuator            | 0.1–60 dB at 5.8–18 GHz   |
| 5     | Attenuation    | 30 MHz WBCO attenuator                  | Attenuator    | Standard piston attenuator     | 0.05–60 dB at 30 MHz      |
| 6     | Attenuation    | Coaxial directional coupler             | Coupler       | –                              | 0.1–60 dB at 30 MHz and 1–18 GHz |
| 7     | Attenuation    | Waveguide directional coupler           | Coupler       | –                              | 0.1–60 dB at 5.8–18 GHz   |
| 8     | Attenuation    | Dual directional coupler                | Coupler       | –                              | 0.1–60 dB at 30 MHz and 1–18 GHz |
| 9     | Attenuation    | Attenuator and signal calibrator        | 30 MHz Receiver | Receiver with built-in 30 MHz attenuator | 0.1–60 dB at 30 MHz |
| 10    | Attenuation    | Power splitter                           | Splitter      | Power divider                  | 0.1–60 dB at 30 MHz and 1–18 GHz |
| 11    | Reflection coefficient/VSWR | Coaxial mismatch | Termination | Coaxial termination | 1.02–5 at 2–18 GHz |
| 12    | Reflection coefficient/VSWR | RF Transfer standard | Sensor | Coaxial thermistor mount | 1.02–5 at 2–18 GHz |
| 13    | Attenuation    | VSWR Meter                               | 1 kHz Receiver | RF Ratiometer                | 0.1–30 dB at 1 kHz       |
| S. No | Parameter                      | Item name          | Item type | Alias name | Range                              |
|-------|--------------------------------|--------------------|-----------|------------|------------------------------------|
| 14    | Reflection coefficient/VSWR    | SWR bridge         | Bridge    | –          | 0.1–60 dB at 1–18 GHz, 1.02–5 at 2–18 GHz |
| 15    | Reflection coefficient/VSWR    | Waveguide standard mismatch | Termination | Waveguide match load | 0.01–0.2 at 5.8–18 GHz |
| 16    | Reflection coefficient         | Coaxial short/open circuit | Reflection standard | Offset short circuit | 0.96–0.99 at 2–18 GHz |
| 17    | Reflection coefficient/VSWR    | Coaxial airline    | Impedance standard | Beadless Airline | 0.01–0.05 at 2–18 GHz |
| 18    | Phase                          | Rotary vane phase shifter | Phase shifter | Variable phase shifter | 0–180 degree (X-Band) |
| 19    | E-Field (V/m)/radiated power density (mW/cm²) | Probe | Antenna | Microwave leakage detector | Probe as per TEC Norm TEC/TP/EMF/001/01.SEP-2009 |
| 20    | Shielding effectiveness        | MRI tester         | Planar material | RF transparency sheet | - |
ii. **Rydberg Atom-Based Quantum-E-Field Standard Sponsored by R&S India Pvt. Ltd.**

CSIR-NPL is continuously working towards the realization of RF E-field strength measurement by utilizing the characteristics of Rydberg alkali atoms. This novel technique relies on the quantum phenomena like Electromagnetically Induced Transparency (EIT) and Autler-Townes splitting (ATS) which are observed in Rydberg alkali atoms under the continuous exposure of laser and RF fields. The idea is that the atoms inside an atomic vapor cell act as antennae (under controlled conditions) which can sense the fields ranging from few MHz to 500 GHz and above. The numerical and analytical simulations of the atomic model have been successfully realized at CSIR-NPL. The experimental results have also been successfully realized by working in collaboration with NISER, Bhubaneswar. The fully functioning facility once established at CSIR-NPL will provide calibration for the E-field probes with traceability to the physical constants such as Plank’s constant and atomic constants. Rohde & Schwarz India Pvt. Ltd. (R&S) has participated with CSIR-NPL in Prime Minister Fellowship for Doctoral Scheme by funding a Ph.D. scholar in this project.

iii. **Establishment of Conducted and Radiated Emission and Electrostatic Discharge (ESD) as a Part of National Facility Creation Project for EMI/EMC Standards**

Conducted and Radiated Emission standard for EMI/EMC compliance as per CISPR 16–2, CISPR 14–1 and CISPR 14–2 are carried out on any household electronic device with a constant signal strength of 10 V/m at different modulation depth for a frequency range of 80 MHz–6 GHz at 10 V/m in CSIR-NPL. In addition, ESD Immunity test as per IEC 61,000–4–2 are also conducted at CSIR-NPL. To calibrate ESD against CSIR-NPL’s primary standard an indigenous instrumentation setup is under development which will have traceability from AC-DC difference measurement of Electromagnetic Metrology.

### 11.4.1.3 Training and Human Resource

Microwave Metrology is also engaged in wide range of human resource related activities in various areas of core competence of the laboratory in terms of training for various stakeholders of the industry and academia from Technical Staff to research scholars/students not only from India but also from SARC nations, gulf countries and African countries as well. The basic objective behind training and human resource activities is to generate a competitive, productive and useful pool of human resource who are better equipped scientifically, technically and administratively to render their services for the society and the country.

Numerous Industrial Training Programs (ITPs) are organized at CSIR-NPL for various fields of Microwave Metrology. The training program generally encompasses various physical parameters in the area of Metrology/Standards, as well as on other
specialized topics. These programs are primarily meant for the personnel belonging to various industries, Testing and Calibration laboratories and other S&T organizations such as ERTL, ETDC, Defence Labs and Industries. The training programs consist of theory lectures on various scientific and technical aspects of the training course including different types of microwave measurement techniques, associated uncertainty followed by practical demonstration and hands-on training on the related instruments/apparatus/machines including uncertainty calculations and ISO17025 Quality system related to microwave metrology. The participants are generally B.E./B.Tech. or M.Sc. as well as Science Graduates or Engineering Diploma Holders. Microwave metrology also engages in summer training programs and internships to undergraduate pre-final year students, graduate training programs along with guiding PhD students.

11.4.2 Future Metrological Road Map

With Ministry of Civil Aviation planning modernisation of Air Traffic Control, Automation of Air Traffic Services and Air Navigation Systems through GPS Aided Geo Augmentation (GAGAN) Project aiming at efficiency and optimum utilisation of the air space, Microwave Metrology can provide a strong technical background for augmenting policies like ‘AAI Start-up Policy’ and Public Procurement policy linked with Local Content (PP-LC) [40, 41].

Similarly, with respect to telecom sector, Telecommunication Engineering Centre (TEC), is in process to join hands with CSIR-NPL to develop indigenous testing instrumentation for mobile phones and wearable devices based on IEEE-1528 2013 and IEC-62209–1,2 standards. In area of 5G and advance communications, CSIR NPL is also a member of EURAMET consortium to develop vector SAR measurement system in the country for the conformity assessment of IEC 62,209–3, 2019 and upcoming modified IEEE 1528 standards which have to be implemented in 2022. Conformity assessment to each and every telecom equipment, either imported or manufactured in India, is essential to ensure quality of these products by TEC under DoT with the help of conformity assessment (CAB) labs. Microwave metrology will not only act as conformity lab for quality assurance, but it will also establish the national measurement traceability for testing equipment used by CABs. Apart from that, with upcoming vector SAR measurement facility, EMI/EMC National Facility and indigenous instrumentation for quantum sensing will address the interconnectivity among various devices within the safe RF exposure limits as per Fourth industrial revolution.

In area of connected devices, around 24 billion devices are projected to be present in the world by around 2020 end according to GSMA (GSM Association) and Machina Research, World’s leading advisor on M2M(Machine to Machine), Internet of Things(IoT) and Big Data, with a combined business impact of around US $ 4.3 trillion. This projection was further increased later by CISCO/Ericsson / ITU to be around 50 billion [42]. With such huge projections, private players and industries
are attracted towards them to explore and exploit wide range of opportunities that
the M2M communication/IoT concept offers. This in turn enables novel business
cases, efficient and improved quality of life. Such networked devices do find their
application across various sectors such as Automotive, Power, Health care, Safety
and Surveillance, Water management, Waste management, Smart homes, Environment
monitoring and pollution control, Intelligent buildings, Smart Cities etc. In
Indian context alone, there may be around 2.6 billion connected devices by 2020.
Power sector (smart metering and smart grid) and Automotive Sector will have
major deployment of M2M devices. CSIR-NPL is continuously striving to establish
a Quality Infrastructure to cater to the metrological needs of IoT/M2M Industry by
constantly striving to develop new and relevant standards.

With reference to EMI/EMC testing, a national facility having national primary
standards with international traceability for immunity to electrostatic discharge,
immunity to radiated RF, immunity to conducted disturbance induced by RF, immu-
nity to fast transients (burst), immunity to surges are being established at CSIR-NPL.
This established facility will not only save foreign exchequer but also cater to different
standardization needs of the country by disseminating the traceability chain and fulfil
broad industrial requirements.

To address the above-mentioned diverse sectors, these sectors can be classified
as per their precise measurement requirements and based on those measurement
requirements, sectors can be broadly divided into the following types of standards
based on their applicability:

- (a) CISPR standards
- (b) IEC standards
- (c) ISO standards
- (d) SAE Electromagnetic Compatibility (EMC) Standards committee
- (e) European standards concerning unwanted electrical emissions
- (f) European standards concerning immunity to electrical emissions
- (g) American standards (FCC, MIL-STD 461, MIL STD-464, MIL-STD 469).

In above two sections a detailed discussion is being carried out on diverse sectors
and their classification for their standards based on their applicability. In Indian
scenario, these sectors belong to ministries and which in turn have regulators to
monitors the current situation and to implement policies. As a part of India’s NMI,
microwave metrology is capable to equip itself with any international standards as
and when required by regulators and/or ministries. CSIR-NPL is constantly in the
pursuit of developing similar and relevant standards suitable for Indian conditions
and thus will be the torchbearer for a successful Make in India program.

In development of these standards suitable to Indian conditions, some of the stake
holders, but not limited to, are as follows:

| (a) Telecommunication electronics centre (TEC) | (i) Ministry of electronics and information technology (MeitY) |
|------------------------------------------------|---------------------------------------------------------------|

(continued)
(continued)

|   |   |   |
|---|---|---|
| (b) | Telecom regulatory authority of India (TRAI) | (j) | Telecom equipment manufacturer association of India (TEMA) |
| (c) | Telecom enforcement resource and monitoring (TERM) | (k) | BEL (Bangalore, Chennai, Panchkula, Ghaziabad, Kotdwar) |
| (d) | Department of telecommunications (DoT) | (l) | Cellular Operators Association of India |
| (e) | Wireless planning and coordinate wing | (m) (n) | ETDC (Bangalore, Chennai) DEAL, Dehradun |
| (f) | Prasar Bharti | (o) | ERTL (North, South, East, West) |
| (g) | Airport authority of India | (p) | SAC, Ahmedabad |
| (h) | All India Radio | (q) | 13 BRD, Palam |

The future metrological roadmap of CSIR-NPL can be better visualised in terms of support to various sectors and various National Missions and programs CSIR-NPL is being a part of.

### 11.4.2.1 Sectorial Support

Microwave metrology provides a strong base for support to many national plans spread across various ministries and departments such as Directorate General of Civil Aviation, Department of Space, Department of Telecommunication, Ministry of Electronics and Information Technology, Defence Ministry, to name a few.

i. **Civil Aviation**: Despite the incredible growth seen in last decade, India continues to be a small player in the international arena. The per capita trips still remain very low in India at 0.04 even by the standards of other emerging markets, such as China (0.15), Brazil (0.25) and Malaysia (0.54). China’s domestic traffic is 5 times that of India’s despite having a population a mere 15% larger [43]. Domestic Traffic can be further augmented with the transit traffic to increase trips per capita. This can be achieved by developing India as an aviation hub between Dubai and Singapore. According to SWOT analysis, by Ministry of Civil Aviation, one of the key weakness to achieve this potential include Lack of R&D; high dependence on foreign suppliers [43]. CSIR-NPL as an NMI can play a pivotal role in addressing this challenge by providing high quality conformity assessment.

ii. **Electrical and Electronics Manufacturing Industry**: Post COVID-19 situation, when a major chunk of manufacturers is keen on relocating their manufacturing units away from China, many countries are eying for setting up their new base of operations in India. India can attract such investments in India by means of favourable tax structures, cheaper land lease, Ease of doing Business etc. NITI Aayog CEO Amitabh Kant’s committee has been setup to come up with suggestions (on lines of Vietnam model) to reduce India’s ‘disability’—or higher production costs—in comparison with China and Vietnam [44]. However, an
important issue still remains to be addressed is that of Quality of the manufactured products. Many such shortcomings are reflected in data of electronics exports and imports. Electronics exports jumped over 38% year-on-year in FY19, but this growth has been majorly on a low base thus still affecting trade balance unfavorably. According to DGIS data, in FY19, India’s electronics export was around $8.4 billion whereas electronics imports grew by approximately 8% to $55.5 billion. Additionally, since most of the industry works on the model of importing components completely or semi knocked-down conditions and shipping them out after assembly, local value addition is very low at about 15–18%, according to industry executives [44]. The lack in growth as compared to competitor nations such as Vietnam (Fig. 11.27) can be attributed to lack of Quality Control Environment. Similar trend has been observed in Export of Telecom Equipment as well (Fig. 11.28).

iii. Telecommunication: A positive step has been taken in this direction by Department of Telecommunication. Prior mandatory testing and certification must be undergone for every telecom equipment, as provided by The Indian Telegraph (Amendment) Rules, 2017. The testing is to be carried out by Indian Accredited Labs, which are designated as CAB (Conformance Assessment Body) by TEC.
and TEC shall issue certificate based upon their test reports in conformance to essential requirements for the equipment. Department of Telecommunication’s (DoT) Technical wing is ISO 9000:2008 certified, Telecommunications Engineering Centre (TEC) [45].

TEC has been identified as the nodal department for implementing the provisions related to procurement of goods, services or works related to the telecommunication sector by Department of Industrial Policy and Promotion (DIPP) [49]. TEC provides technical support to DoT and other government departments and formulates Generic Requirements (GR) for telecom equipment, networks, systems and services to be deployed in Indian Telecom Network, on the basis of International Standards [49]. TEC has published list of Essential requirements under Mandatory Testing and Certification of Telecom Equipment (MTCTE), test procedure for EMF measurement, Electromagnetic Interference and Electromagnetic Compatibility (EMI/EMC) compliance testing and so on. Addressing the safety concerns related to microwaves, and for the safety of the public, DOT has prescribed a certain EMF exposure from base station installations in accordance with International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines. To give effect to this, TEC has published ‘Test procedure for measurement of electromagnetic fields from base station antenna’, which serves as detailed procedure for the certificate of compliance of EMF exposure norms by the Telecom Service Providers (TSPs) and audited by the Licensed Service Area (LSA) Units of the Department of Telecommunications (DOT) [50]. Under MTCTE (Mandatory Testing and Certification of Telecom Equipment) program from Department of Telecommunications (DoT) it is mandatory to test and certify all telecom equipment which are produced in India or imported from abroad. In this scenario CSIR-NPL will prove to be an important collaborator of TEC to establish a Quality Infrastructure in India in the field of telecom equipment testing and certification.

iv. **Electronics**: National Policy on Electronics (NPE) envisaging a US$ 400 billion electronics manufacturing industry in the country by 2025 [51]. Through this Policy India is envisioned to be positioned as a global hub for Electronics System Design and Manufacturing—(ESDM) by encouraging and driving capabilities in the country for developing core components, including chipsets, and to create an enabling environment for the industry to compete globally. Simultaneously, NATRiP (National Automotive Testing and R&D Infrastructure Project) is setting up state-of-the-art Testing [52], Validation and R&D infrastructure in the country for Automotive Sector synergizing Make in India and FAME II (Faster Adoption and Manufacturing of Electric Vehicles) efforts.

v. **Defense**: Role of Quality Infrastructure becomes more important keeping in mind the new Defence Procurement Procedure (DPP) and policy 2020, released by The Ministry of Defence (MoD) [53]. In line with government’s “Make in India” initiative, in a bid to reduce reliance on imports and targeting to boost indigenous defence capability, DPP amends existing military procurement rules
accordingly. It has proposed enhancement of indigenous content requirements in foreign procurements too.

11.4.2.2 National Mission and Programs

Following national program can be supported by microwave metrology based on its technical capabilities:

i. **Aviation**: Keeping in mind the vast market potential of civil aviation, Airport Authority of India (AAI) has recently set up a Civil Aviation Research Organization (CARO) at Hyderabad to significantly boost in-house research capabilities within AAI [40]. On similar lines, AAI is planning to establish Test Equipment Calibration lab at Hyderabad. CSIR-NPL, which is an apex body in this field of calibration, can play an active role by having a collaboration to help AAI establish and get NABL accreditation for the Test Equipment Calibration lab being established at Hyderabad to meet the calibration requirements of AAI Communication, Navigation and Surveillance (CNS) test equipment to comply with the DGCA’s Civil Aviation Requirements (CAR). AAI calibration lab at Hyderabad to the extent that all equipment used by 29 ATC centers across India could have measurement traceability through NMI including ISO/IEC 17,025:2017 accreditations from NABL, SOPs for Calibrators and calibration process, Inter laboratory comparison (ILC)/ Proficiency Testing (PT) on established parameters to build confidence in measurement with manpower training to operate, control and calibrate instrumentation from the lab.

ii. **Telecommunication**: MTCTE program of TEC is based on CABs which are private partners under TEC (PPP model). Success of MTCTE program will be highly dependent (Fig.11.29) on TEC vigilant procedures. However, as NMI of India, microwave metrology can play an essential role to implement this program successfully with its measurement capabilities on those parameters. Microwave metrology will not only monitor the measurement capabilities of these designated CABs but also provide them with assistance in terms of measurement traceability, trained manpower, and surveillance, thus saving foreign exchequer. A surveillance mechanism forms an essential component to check the quality of products on random basis under MTCTE program and also under proposed model lab of TEC. A flow diagram for traceable surveillance is provided in Fig. 11.30.

CSIR-NPL can plan together with TEC regarding CAB Traceability with following technological output:

(a) Tissue Equivalent Liquid required for Specific Absorption Rate Testing and Calibration will be ready can be prepared by CSIR- NPL under BND Program

(b) Gigahertz Transverse Electromagnetic Cell and Chambers can be developed exclusively for testing of EMI/EMC Measurement and Certification for existing and upcoming smart telecom instrumentation
Fig. 11.30  Role of CSIR-NPL as NMI in Indian telecom quality infrastructure under MTCTE program

Fig. 11.31  Role of CSIR-NPL as NMI in the legal metrology and market surveillance
 iii. **EMI/EMC National Facility for Primary Standards**: CSIR-NPL in its endeavor towards India’s prosperity and quality of life through continuous research and development and disseminating measurement capabilities to industry, government, strategic and academia has started working towards establishment of National Facility for primary EMI/EMC Standards. Conducted and Radiated Emission Testing Facility has been established, which is to be soon followed by Electrostatic Discharge Testing facility and other parameters such as Surge, Burst, Harmonics, Flicker etc. within next 1 year.

National Facility for primary standards for EMI/EMC testing has the following objectives:

(a) To develop, maintain and upgrade national primary Electromagnetic Interference and Electromagnetic Compatibility (EMI/EMC) standards of international level and disseminate traceability of measurement through apex level calibration to the industries- power sectors, state electricity boards, calibration laboratories and allied industries in India and to SAARC countries.

(b) To add new CMCs as per requirements of industries and calibration laboratories.

(c) Participation in international intercomparisons with other NMIs to ensure compatibility with international standards.

(d) Add CMC for these parameters to BIPM so that international trade barrier can be removed to promote Make in India.

(e) All International Standards will be complying with these standards such IEC, MIL, CISPR and IEEE for calibration and testing of wearable and smart devices.

National Programs and policies of microwave metrology at CSIR-NPL are based on the classification of devices based on their application in accordance with CISPR (International Special Committee on Radio Interference):

(a) General purpose applications (Classes A or B, Group 1)
   - Laboratory equipment
   - Medical electrical equipment
   - Scientific equipment
   - Industrial process measurement and control equipment
   - Semiconductor manufacturing equipment etc.

(b) ISM RF applications (Classes A or B, Group 2)
   - Microwave-powered UV irradiating apparatus
   - Microwave lighting apparatus
   - Induction cookers
   - Dielectric heating equipment
   - Microwave ovens
| Test name                              | Standards                                      |
|----------------------------------------|------------------------------------------------|
| E-Field                                | IEEE 1309 -2013                                |
| Radiated power density                 | IEEE C95.1, 2019                               |
| Specific absorption rate (SAR)         | IED 62,209–1,2,3                               |
| Conducted and radiated emission        | CISPR 32 (2015) or CISPR 22 (2008) Class-B    |
| Immunity to electrostatic discharge    | IEC-61,000–4.2 (2008)                         |
| Immunity to radiated RF                | IEC 61,000–4.3 (2010)                         |
| Immunity to fast transients (burst)    | IEC 61,000–4.4 (2012)                         |
| Immunity to surges                     | IEC 61,000–4.5 (2014)                         |
| Immunity to conducted disturbance induced by radio frequency fields | IEC 61,000–4.6 (2013) |
| Immunity to voltage dips and short interruptions | IEC 61,000–4.1 1 (2004) |

- Medical electrical equipment
- Electro-discharge machining (EDM) equipment etc.

Following Table 11.8 contains a non-exhaustive list of standards that are tested at CSIR-NPL or are at final stages:

iv. **Defence**: CSIR-NPL aims to play the pivotal role through development of standards similar to MIL-STD of USA in field of EMI/EMC, SAR evolution, Antenna calibration, radome testing, anechoic chamber calibration, aerospace equipment testing E-Field probes and sensors calibration, and strategic material characterization so as to achieve the objective of making India self-reliant and a global manufacturing hub as envisioned by our honorable Raksha Mantri [54]. CSIR-NPL will continuously strive to support Indian government to develop the eco-system for indigenous defence production and thus empowering the Indian private industry including MSMEs. CSIR-NPL will be the catalyst for improving the international competitiveness for Indian Industries and thus give impetus to India’s economic growth and realize our global ambitions.

### 11.5 Economic Impact

An International Civil Aviation Organization (ICAO) study attributes over 3.6% of global GDP to the air transport component of civil aviation [55]. In the Indian context, in last ten years, the civil aviation sector has grown at a tremendous pace and India has emerged as the 9th largest civil aviation market in the world [43]. According to another ICAO estimate, for every USD 1 of gross value added (GVA) directly created by the air transport sector, USD 3.8 of economic activity was supported elsewhere.
and approximately 6.4 jobs are dependent on every person directly employed in the aviation sector and in tourism made possible by aviation [55]. New industries/services for post covid-19 situation, wherein wireless tracking devices are going to play a major role for contact tracing especially for foreign nationals are the additional job creators linked to aviation sector.

The market for microwave/wireless devices encompasses IoT devices, Bluetooth devices, wireless telecommunication devices, Wi-Fi devices, RFID devices, smart sensors and so on, each witnessing an ever increasing CAGR over the last decade. With an expected growth of approximately 31 times from 0.06 billion IoT devices in India (base year of 2016) to 1.9 billion devices in 2020 end, it translates into a revenue opportunity of $9 billion by 2020 from the 2016 number of $1.3 billion, nearly 700% increment [56]. Government of India based on its draft IoT policy is targeting to create a $15 billion IoT industry in India by 2020 end [57]. To this end GoI has established Centre of Excellence for IoT in Bangalore in collaboration with software technology parks of India (STPI) with industry participation from companies such as Intel, NXP, Qualcomm, Texas Instruments, and others [58].

From the prospect of wireless devices providing internet, the number of internet subscribers in the country increased at a CAGR of 45.74% during FY06-FY19 to reach 636.73 million in 2018–19, second largest online market in the world, ranked only behind China. The internet subscribers reached 687.62 million till September 2019. Total wireless data usage in India grew 10.58% year-on-year to 19,838,886 terabytes between July–September 2019 [4]. However, the overall internet penetration is still at 31%, skewed in favour of urban India, which has ~70% internet penetration. Rural India is still underpenetrated with only 17% penetration. With a total rural population of ~906 million, approximately 750 million users still do not use internet [59]. Over the last few years, increase in internet penetration has been driven mostly by availability of cheaper smartphones. More than 92% of rural users and 77% urban users have been using mobile as primary device for accessing internet through cellular data connections [59].

National Primary Facility for EMI/EMC can help with required EMI/EMC certifications to broadly cater for Automobile Sector under FAME 2 (Faster Adoption and Manufacturing of Electric Vehicles in India Phase 2) [60], Telecom Equipment (under MTCTE) and electronic equipment especially IoT, robotics and drone-based devices. Currently, nationwide more than 300 labs are engaged in EMI/EMC work, with an expenditure from each lab of at least 30 Lakh INR annually on EMI/EMC Parameters Traceability (300 × 30 = 9000 Lakhs). This is the result of majority of calibration laboratories across India using purely imported equipment and their traceability certificate is also imported due to lack of traceability on essential telecom parameters.

All these electronic industries need a dedicated, internationally traceable EMI/EMC standards and certification infrastructure to be export ready. This will give impetus to Make in India Initiative, FAME initiative by NITI Aayog, Export capability for Indian ESDM (Electronics System Design and Manufacturing) Sector by reducing technical barriers to trade, National Strategy for Artificial Intelligence
and National Plan for Smart Electrical Metres, indirect employment generation and save at least 15 million USD foreign exchequer annually.

India has the 3rd largest armed forces and 10th largest Defence expenditure in the world. India spends around 1.5% of its GDP to Defence Budget (without the pensions) \[61\]. The Budget for Defence has increased by almost 5.8% to reach 3.37 lakh crore as the defence budget for 2020–21, the current financial year. India currently procures approximately 70% of its equipment needs from abroad. With a Compound annual growth rate (CAGR) of 18%, Indian Defence and Civil Aviation market would put the country, in very near future, among one of the top five Defence and Civil aviation markets. To strengthen the dedicated defence manufacturing corridors, internationally traceable EMI/EMC standards and certification infrastructure will not only make indigenously developed critical sub-components more reliable, but also export ready.

11.6 Conclusion

In the field of measurements in Microwave, CSIR-NPL deals with various parameters such as microwave power, attenuation, impedance, and shielding effectiveness for the frequencies ranging from 9 kHz to 110 GHz of electromagnetic spectrum. These parameters serve as a base for rapid progress in the field of electrical and electronics devices, and their interconnectivity that propel us towards Fourth industrial revolution. The concept of IoT driven wireless interconnectivity of smart homes, smart offices, smart cities and smart health care including upcoming quantum communication revolution will only be successful if CSIR-NPL will equip to provide traceability and certification on these smart technologies. Their applications are visible in almost every sector such as manufacturing industries, educational institutes, strategic sectors, biomedical devices, hospitals and households. Surprisingly, most of these advanced devices are imported into India and are not locally manufactured. In spite of government’s all efforts to ‘make India an electronics manufacturing hub which triggered several national programs and policies such as NEP (2019), MTCTE program of DoT, DPP policy (2020), Make in India policy and Aatmanirbhar Bharat, Indian manufacturers are still struggling to reduce import export ratio. The reason for such import imbalance lies with unavailability of high-end sophisticated instruments, which in turn is due to lack of quality infrastructure and cost ineffectiveness. Microwave metrology is capable to provide traceability, calibration and technical services to all manufacturing units in India associated with electrical, electronics and telecom via reference labs so that the quality of electronics systems could be enhanced and thus reduce the trade deficit.

Microwave metrology deals with defence, space, telecom and microwave driven industry related testing and calibration parameters as per IEEE, IEC and MIL standards to cater these sectors as per international norms. CSIR-NPL serves these sectors as per existing standards for microwave power, attenuation, impedance to E-Field, radiated power density and SAR; at the same time, it is upgrading itself in term
of SI traceable Quantum E-field measurement, vector SAR and measurement standards for 5G so that future standardisation challenges could be addressed proactively. Microwave metrology is capable to provide technical/technological consultancy in the domain of E-field generators, E-Field sensors, SAR probes, tissue equivalent liquids and SAR measurement systems as per IEEE 1528 and IEEE 1309 standards. With regard to various national programs and policies, microwave metrology can play a vital role in MTCTE of TEC, NEP program of MeitY, ATC certification program of DGCA and defence calibration required for radiated EM parameters. Microwave metrology can provide technical and technological support in the form of indigenously designed and developed GTEM, tissue equivalent liquid and SAR measurement system. In area of advance telecom standards such as 5G and beyond, the microwave metrology at CSIR-NPL is part of European consortium and is in process to establish vector SAR measurement system indigenously so that Indian telecom industries could be served as per upcoming standards 62,209–3-2019 applicable from 2022.

Finally, the projected impact of Microwave metrology on India’s GDP is around 12–18% and with its indirect contributions encompassing R&D support to the manufacturing sector, certification to the end products and saving foreign exchequer by developing various indigenous parameters, it could supplement the GDP by as much as 26%. Thus, Policy makers in active collaboration with CSIR-NPL for Microwave metrology at policy formulation stage can ensure a robust quality infrastructure for the nation within safe EM exposure limits.

Acknowledgements The authors would like to acknowledge all the ex-colleagues; present colleagues Ms. Sunidhi Madan, Mr. Anurag Katiyar, Ms. Mandep Kaur, Mr. Anish Bhargav, Ms. Archana Sahoo, Ms. Jyoti Chauhan, Ms. Swati Kiumari, Mr. Mange Ram and Mr. Amreek Singh; and students of CSIR-NPL for their contributions in establishing Electromagnetic Metrology. We would also like to thank the stake holders Department of Legal Metrology, SAC-ISRO, PGCIL, STQC Labs, TEC-DoT, AAI, LM, M/s R&S India Pvt Ltd., M/s Valliant Comm. Pvt Ltd. and many others for their continuous support and collaboration in the National mission endeavours for Electromagnetic Metrology dissemination pan-India.

References

1. G. Elert, The Electromagnetic Spectrum, The Physics Hypertextbook (2016)
2. Business Standard, Focus on ‘Make in India (2014). [Online] Available https://www.business-standard.com/article/government-press-release/focus-on-make-in-india-114092501206_1.html
3. Electronic Industries Association of India, Industry Overview: Growth of Electronics Sector (2019). [Online] Available https://www.elcina.com/overview.php
4. India Brand Equity Foundation, Indian telecom industry analysis. India Brand Equity Foundation, Mar (2020). [Online] Available https://www.ibef.org/industry/indian-telecommunications-industry-analysis-presentation
5. Economic Times, Appliances and consumer electronics industry expected to double to Rs 1.48 lakh crore by FY25. Nov (2019) [Online] Available https://economictimes.indiatimes.com/
industry/cons-products/durables/appliances-and-consumer-electronics-industry-expected-to-double-to-rs-1-48-lakh-crore-by-fy25/articleshow/72183954.cms?from=mdr#:~:text=Appliances%20and%20consumer%20electronics%20industry%20manu
6. Tradingeconomics.com, India exports of electronic goods (2020). [Online] Available https://tradingeconomics.com/india/exports-of-electronic-goods
7. Eletimes.com, Indian Electrical equipment industry records highest growth of 12.8% in seven years,” 18 Jun (2018). [Online] Available https://www.eletimes.com/indian-electrical-equipm
8. G. Das, Make in India: consumer electronics manufacturing to grow at 18%. 7 May (2020). [Online] Available https://www.businesstoday.in/current/economy-politics/make-in-india-con
9. U. Mishra, PM Modi’s Aatmanirbhar Bharat Abhiyan economic package: here is the fine print. 14 May (2020). [Online] Available https://indianexpress.com/article/explained/narendra-modi-coronavirus-economic-package-india-self-reliance-6406939/
10. Deity, Cabinet approves the proposal of national policy on electronics 2019, Feb (2019). [Online] Available https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1565285
11. E. Bureau, “India unveils Rs 50,000 crore schemes to attract electronics makers,” 3 Jun (2020). [Online] Available https://economictimes.indiatimes.com/tech/hardware/govt-sta
12. CSIR-NPL, https://www.nplindia.in/data/npldjvsec.pdf. [Online]
13. S. Ahmad, M. Charles, D. Allal, P.S. Negi, V.N. Ojha, Realization of 2.4 mm coaxial microcalorimeter system as national standard of microwave power from 1 MHz to 50 GHz. Measurement 116, 106–113 (2018)
14. R. Swarup, J.R. Anand, P.S. Negi, On 30 MHz TE11 mode piston attenuator. Rev. Sci. Instrum. 72, 1858 (2001)
15. S. Dubey, N. Narang, P. Negi, V. Ojha, Microwave measurement systems. In: LabVIEW Based Automation Guide for Microwave Measurements, Springer Briefs in Electrical and Computer Engineering (Singapore, Springer, 2018)
16. EURAMET, Guidelines on the Evaluation of Vector Network Analysers (VNA) EURAMET Calibration Guide No. 12 Version 3.0 (Euramet, Germany, 2018)
17. R. J. Collier and A. Skinner, Microwave measurements vol 12. (IET , United Kingdom, 2007)
18. G. Monasterios, H. Silva, Key comparison SIM.EM.RF-K5b.CL: scattering coefficients by broad-band methods, 2 GHz–18 GHz — type N connector,” Metrologia (2016)
19. N. Narang, S. Dubey, P.S. Negi, V. Ojha, Accurate and precise E-field measurement for 2G and 3G networks based on IEEE Std. 1309–2013. Microwave Opt. Technol. Lett. 57(7), 1645–1649 (2015)
20. N. Narang, S.K. Dubey, P.S. Negi, V.N. Ojha, Design and characterization of microstrip based E-field sensor for GSM and UMTS frequency bands. Rev. Sci. Instrum. 87(12), 124703 (2016)
21. Final report on supplementary comparison EUROMET.EM.RF-S25 (EURAMET project 819): Comparison of electrical field strength measurements above 1 GHz,” Metrologia (2011)
22. M. Kanda et al., International comparison GT/RF 86–1 electric field strengths: 27 MHz to 10 GHz. IEEE Trans. EMC 42, 190–205 (2000)
23. N. Narang, Computational Modeling and Measurement of RF Specific Absorption Rate—PhD thesis,” (AcSIR, CSIR National Physical Laboratory, New Delhi, 2017)
24. BIPM, “KCDB BIPM;” [Online] Available https://www.bipm.org/kcdb/
25. CSIR-NPL, New Delhi, “Calibration Charges: D6.02c, LF&HF voltage, current and microwave metrology,” [Online] Available https://www.nplindia.in/calibration-charges-d602c-lf-hf-voltage-current-and-microwave-metrology-wef01042019
26. K. Patel, P. S. Negi and R. Swarup, “Final report on APMP supplementary comparison P1-APMP. EM. RF-S3: APMP comparison of 50 ohm coaxial mismatches,” Metrologia 49(1A) (2012)
27. C. Eio, Final report on key comparison CCEM. RF-K5b. CL (GT-RF/92–3): scattering coefficients by broad-band methods, 2–18 GHz, Type N connector. Metrologia (2000)
28. G. Qiulai et al., Final report on APMP attenuation key comparison APMP. EM. RF-K19. CL: attenuation at 60 MHz and 5 GHz using a type N step attenuator. Metrologia (2010)

29. H.S. Rawat, S.K. Dubey, V.N. Ojha, Distinction between double electromagnetically induced transparency and double Autler–Townes splitting in RF-driven four-level ladder $^{87}$Rb atomic vapor. J. Phys. B: At. Mol. Opt. Phys. 51(15) (2018)

30. C.L. Holloway et al., Gourd broadband rydberg atom-based electric-field probe for SI-traceable, self-calibrated measurements. IEEE Trans. Antennas Propag. 62(12), 6169–6182 (2014)

31. H.S. Rawat, S.K. Dubey, V.N. Ojha, Polarization dependence of interferences inside rubidium atomic vapor governing microwave vector E-field metrology. JOSA B 36(12), 3547–3554 (2019)

32. I. Standards, IEEE Std C95.6™ —IEEE standard for safety levels with respect to human exposure to electromagnetic fields, 0–300 GHz,” IEEE Standards (2019)

33. I. Standards, IEEE 1528-IEEE recommended practice for determining the peak spatial-average specific absorption rate (SAR) in the human head from wireless communications devices: measurement techniques. IEEE Standards (2013)

34. I. Standards, ICNIRP, “Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz),” Health Phys. (1998)

35. A. Djamel, “SAR measurement Using Vector Probes Short Name: Vector SAR, Project Number: 16NRM07,” (2017). [Online] Available https://www.euramet.org/research-innovation/search-research-projects/details/?tx_eurametctcp_project[project]=1478&tx_eurametctcp_project[controller]=Project&tx_eurametctcp_project[action]=show

36. I. Standards, IEC/IEEE draft international standard—recommended practice for measurement procedures for the assessment of specific absorption rate (SAR) of human exposure to radio frequency fields from hand-held and body-worn wireless communication devices (2019). [Online] Available https://standards.ieee.org/project/62209-1528.html

37. W.H. Bailey et al., Synopsis of IEEE Std C95.1TM-2019 IEEE standard for safety levels with respect to human exposure to electric, magnetic, and electromagnetic fields, 0 Hz to 300 GHz. IEEE Access 7, 171346–171356 (2019)

38. D.K. Aswal, Quality infrastructure of India and Its importance for inclusive. MAPAN 35(2), 139–150 (2020)

39. Wireless testing market by offering (Equipment, Services), technology (Bluetooth, 2G/3G, 4G/5G, Wi-Fi), application (Consumer Electronics, Automotive, IT and Telecommunication, Medical Devices, Aerospace and Defense) and region—global forecast to 2024 (2018). [Online] Available https://www.marketsandmarkets.com/Market-Reports/wireless-testing-market-128820153.html; www.marketsandmarkets.com.

40. Airport Authority of India, AAI Startup Initiative—Innovate For Airports (2018). [Online] Available https://www.aai.aero/en/important-links/aai-startup-initiative-innovate-airports

41. Airport Authority of India, AAI draft policy for public procurement linked with local content (2017). [Online] Available https://www.aai.aero/en/corporate/resources

42. CISCO, The internet of things: how the next evolution of the internet is changing everything. [Online]. Available https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoT_IBSG_0411FINAL.pdf

43. Ministry of Civil Aviation, India, Strategic Plan. [Online] Available https://www.civilaviation.gov.in/strategic-plan

44. K.B. Pattanayak, R. Ranjan, Financial Express, 19 Aug (2019). [Online] Available https://www.financialexpress.com/economy/kant-panel-aims-for-vietnam-like-model-for-mobile-phone-exports/1679103/

45. Telecommunications Engineering Center, “Mandatory Testing and Certification of Telecom Equipments (MTCETE).” [Online] Available https://www.tec.gov.in/mandatory-testing-and-certification-of-telecom-equipments-mtce/

46. S. Kantha, “Make-in-India lessons: why are vietnam’s electronics exports ten times that of India’s?,” 22 May (2017). [Online] Available https://thewire.in/economy/india-vietnam-trade-exports
47. United Nation Conference on Trade and Development, Vietnam Exports. [Online] Available https://www.ceicdata.com/en/indicator/vietnam/exports-ict-goods;www.ceicdata.com
48. United Nation Conference on Trade and Development, India Exports. [Online] Available https://www.ceicdata.com/en/indicator/india/exports-telecommunication-equipment;www.ceicdata.com
49. Telecommunications Engineering Centre, “Public Procurement (Preference to Make in India) Order (2017).” [Online] Available https://www.tec.gov.in/public-procurement-preference-to-make-in-india-order-2017/
50. Telecommunications Engineering Centre, “Test procedure For Measurement of Electromagnetic Fields,” Jun (2018). [Online] Available https://www.tec.gov.in/test-procedure-for-measurement-of-electromagnetic-fields/
51. Business Standard, “Cabinet approves proposal of National Policy on Electronics 2019,” Business Standard, Feb (2019). [Online] Available https://www.business-standard.com/article/business-standard/cabinet-approves-proposal-of-national-policy-on-electronics-2019-119022000282_1.html
52. National Automotive Testing and R&D Infrastructure Project (NATRiP), Vision and Mission (2011). [Online] Available https://www.natrip.in/
53. P. DAS, “India’s defence procurement policy 2020,” Observer Research Foundation, Apr (2020). [Online] Available https://www.orfonline.org/expert-speak/indias-defence-procurement-policy-2020-old-wine-in-a-new-bottle-64673#:~:text=The%20Ministry%20of%20Defence%20(MoD,%E2%80%9CMake%20in%20India%E2%80%9D%20initiative
54. Ministry of Defence, “Defence Procurement Procedure 2020,” Press Information Bureau of India, Mar (2020). [Online] Available https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1607400
55. International Civil Aviation Organization (ICAO), “Aviation Benefits Report 2019, International Civil Aviation Organization (ICAO),” Sept (2019). [Online] Available https://www.icao.int/sustainability/Pages/IHLG.aspx
56. Deloitte, Technology, Media and Telecommunications Predictions 2018—India edition (2018). [Online] Available https://www2.deloitte.com/content/dam/Deloitte/in/Documents/technology-media-telecommunications/in-tmt-predictions-2018-noexp.pdf
57. Department of Electronics and Information Technology, Draft Policy on Internet of Things (2016). [Online] Available https://www.mygov.in/sites/default/files/master_image/Revised-Draft-IoT-Policy-2.pdf
58. Economic Times, “STPI Announces IoT Centre of Excellence in Bengaluru,” Dec (2019). [Online] Available https://economictimes.indiatimes.com/small-biz/startups/newsbuzz/stpi-announces-iot-centre-of-excellence-in-bengaluru/articleshow/72383263.cms?from=mdr
59. Internet and Mobile Association of India , Internet in India—An Iamai and Kantar IMRB Report (2016). [Online] Available https://cms.iama.in/Content/ResearchPapers/a7d38c59-689b-4764-9c34-f90ec17f5a2c.pdf
60. Department of Heavy Industries, Ministry of Heavy Industries and Public Enterprises, FAME India Phase 2 (2019). [Online] Available https://fame2.heavyindustry.gov.in/content/english/11_1_PolicyDocument.aspx
61. Economic Times, “Marginal increase in defence budget could mar new acquisitions,” Economic Times, Feb (2020). [Online] Available https://economictimes.indiatimes.com/news/defence/marginal-increase-in-defence-budget-could-mar-new-acquisitions/articleshow/73839394.cms#:~:text=Without%20the%20pension%20or%20defence%20acquisitions%20the%20revenue%20head