Chapter 21

# High Power Microwave Effects & Safety

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Microwave devices find usage in our day to day life very commonly. For this reason effects of microwaves on other electronic devices and human safety become very important to discuss. IEMI sources are increasing the power ranges to Gigawatts with time, hence its effects on electronic circuits and systems as well as human safety may become much more catastrophic and proper safety measures should be taken [1, 2].

High power microwave effects can be catastrophic and spectacular in nature. Lightning of LED bulbs and fluorescent tubes is one of the very common effects which can be observed near high power microwave sources. A very commonly quoted tragic incident for IEMI effects is Aircraft carrier Forrestal accident on July 29, 1967, which occurred due to IEMI illumination of missile cable with improperly mounted shielded connector. This accident resulted in $72 million of monetary damage along with 134 men dead or missing [3].

High power microwave effects are to be classified into three categories: heating effects, biological effects, and effects on electronic circuits/systems. All these three along with coupling mechanisms and electronic vulnerability and susceptibility will be discussed in this chapter.

## 21.1. Heating Effects

Heating effects of microwave are caused due to dielectric heating phenomena. Dielectric heating is very commonly used in different industrial setups. Microwave oven is a very commonly used device used for household applications.

Complex permittivity of a dielectric material is given by following equation,

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{21.1}$$

Here

$$\varepsilon'' = \varepsilon' tan\delta - \frac{\sigma}{\omega} \tag{21.2}$$

Here $tan\delta$ is called loss tangent and conductivity of the material is $\sigma$, $\varepsilon'$ is real part of dielectric constant, $\omega$ is angular frequency. Power absorbed into heat per unit volume is given by,

$$p = (\omega\varepsilon' tan\delta)E^2 + \sigma E^2 \tag{21.3}$$

Where $E$ is the electric field strength of microwave.

## 21.2. Biological Effects

Microwave radiation causes biological effects mainly due to power absorption through dielectric heating in body tissues which results in temperature increase. Biological effects on humans and animals are complex, because of the internal regulation mechanisms involved in body and non-uniform power absorption. Different type of biological effects may be there due to microwaves ranging from chromosomal alterations, mutagenesis, activation and inactivation of virus to behavioural effects [3, 6]. Some of these effects are tabulated in Table 21.1. Most of the studies for biological effects of microwaves has been performed on rodents and mice, full-fledged studies on humans are not available [4-6, 1].

Table 21.1. Biological effects of microwave and exposure levels [3].

| **Effect** | **Observation** | **Exposure Level** |
|---|---|---|
| Mutagenesis | No effects observed in rodents. | $< 10$ mW/cm$^2$ |
| Fetal Development | No effects observed | $< 10$ mW/cm$^2$ |
| Central Nervous System | Transient function changes occur | $< 10$ mW/cm$^2$ |
| Behavioural Effects | Effects on rodents occur | 5 mW/cm$^2$-20 mW/cm$^2$ |
| Immunity System | Initial stimulation of leukocyte production seen in rodents | $< 10$ mW/cm$^2$ |
| Auditory response | Audible clicks perceived under modulated illumination | $> 1$ W/cm$^2$ |
| Ocular effects | Epithelial and stromal injuries to human eyes expected | 10 mW/ cm$^2$ at 35-107 GHz |
| Skin sensitivity | Warming sensation occurs | 1 mW/ cm$^2$ at 35-107 GHz<br>27 mW/cm$^2$ at 2.45 GHz |

## 21.2.1. Specific Absorption Rate

Specific Absorption Rate (SAR) is a metric used for microwave absorbed by body/target due to microwave power expressed in watts/kilogram (W/kg). SAR is defined by following equation.

$$SAR = \frac{\sigma}{\rho}|E|^2 \tag{21.4}$$

where σ is the tissue conductivity, $\rho$ is the mass density, and $E$ is the root mean square electric field intensity at the point of absorption. SAR quantifies whole body absorption of power and is used for determination of total energy absorbed. From sensitivity point of view, brain is the human body part which is maximum prone to microwave effects. Microwave absorption rate for complete body is maximum in 20 MHz to 100 MHz frequency range. In 350 MHz - 400 MHz range, enhanced SAR is observed in palate region and in upper part of back of the neck. At 2.45 GHz, SAR is considerably higher in the neck, the legs, and the front elbow [7].

## 21.2.2. Microwave Induced Auditory Effect

Depending on pulse width and repetition rate pulsed microwave different type of audible sounds like click, buzz or chirp are observed by humans. Pulses from 1-32 µs with a frequency of 2.45 GHz with energy density 40 µJ/cm$^2$ can cause this kind of response. Possible reason attributed to this kind of response is generation of thermo elastic wave of pressure in brain tissues that drives receptors of inner ear [1, 3, 10].

### 21.2.3. Microwave Safety Standards

Microwave safety standards for maximum permissible exposure limit are a function of frequency. These limits for controlled areas and uncontrolled areas are listed in table 21.2 and table 21.3. Controlled areas are the areas which have limits defined for people having occupational exposure to these microwave radiations, these limits in general are at higher level than that for uncontrolled areas. Limits defined for uncontrolled areas are defined for general public. The Occupational Safety and Health Administration (OSHA) has adopted ANSI standard C 95.1, as per tables 21.2 and 21.3 [8].

Table 21.2. Maximum allowable limit of microwave exposure for people in controlled environment [8].

| **Frequency Band** | **Electric Field Intensity root mean square value (V/m)** | **Magnetic field Intensity root mean square value (A/m)** | **Power density root mean square value (S) (E field, H field) (W/m²)** | **Averaging Time (seconds)** |
|---|---|---|---|---|
| 0.1-1.0 MHz | 1842 | $16.3/f_{MHz}$ | $(9E3, 1E4/f_{MHz}^2)$ | 360 |
| 1.0-30 MHz | $1842/f_M$ | $16.3/f_{MHz}$ | $(9E3/f_{MHz}^2, 1E4/f_{MHz}^2)$ | 360 |
| 30-100 MHz | 21.4 | $16.3/f_{MHz}$ | $(10, 1E4/f_{MHz}^2)$ | 360 |
| 100-300 MHz | 21.4 | 0.163 | 10 | 360 |
| 0.3-3 GHz | - | - | $f_{MHz}/30$ | 360 |
| 3-30 GHz | - | - | 100 | $1177.8/f_{GHz}^{1.079}$ |
| 30-300 GHz | - | - | 100 | $151.44/f_{GHz}^{0.476}$ |
| *$f_{MHz}$ is frequency in MHz and $f_{GHz}$ is frequency in GHz.* | | | | |
| For uniformly illuminated body rms field strengths can be used, in case of nonuniform illumination rms power density spatially averaged over illuminated body are to be used [8]. | | | | |

Table 21.3. Maximum allowable limit of microwave exposure for people in uncontrolled environment [8].

| **Frequency Band** | **Electric Field Intensity root mean square value (V/m)** | **Magnetic field Intensity root mean square value (A/m)** | **Power density root mean square value (S) (E field, H field) (W/m²)** | **Averaging Time (E field, H field) (min)** |
|---|---|---|---|---|
| 0.1-1.34 MHz | 614 | $16.3/f_{MHz}$ | $(1000, 10000/f_{MHz}{}^{2})$ | (6,6) |
| 1.34-3.0 MHz | $823.8/f_{MHz}$ | $16.3/f_{MHz}$ | $(1800/f_{MHz}{}^{2}, 10000/f_{MHz}{}^{2})$ | $(f_M{}^2/0.3,6)$ |
| 3.0-30 MHz | $823.8/f_{MHz}$ | $16.3/f_{MHz}$ | $(1800/f_{MHz}{}^{2}, 10000/f_{MHz}{}^{2})$ | (30,6) |
| 30-100 MHz | 27.5 | $158.3/f_{MHz}{}^{1.668}$ | $(2, 9400000/f_{MHz}{}^{2})$ | $(30, 0.0636 f_M{}^{1.337})$ |
| 100-400 MHz | 27.5 | 0.0729 | 2 | (30,30) |
| 0.4-2 GHz | - | - | $f_{MHz}/200$ | 30 |
| 2-5 GHz | - | - | 10 | 30 |
| 5-30 GHz | - | - | 10 | $150/f_{GHz}$ |
| 30-100 GHz | - | - | 10 | $25.24/f_{GHz}{}^{0.476}$ |
| 100-300 GHz | - | - | $(90f_{GHz}\text{-}7000)/200$ | $5048/[(9f_{GHz}\text{-}700)f_{GHz}{}^{0.476}]$ |
| *$f_{MHz}$ is frequency in MHz and $f_{GHz}$ is frequency in GHz.* | | | | |
| For uniformly illuminated body rms field strengths can be used, in case of non-uniform illumination rms power density spatially averaged over illuminated body are to be used [8]. | | | | |

In case of pulsed power, biological effects observed can be different from CW power due to rate of energy absorption being different. These effects are not always a function of average power observed.

## 21.2.4. Effects of Microwave on Electronics

Effects of microwave on electronic circuits can be of different types depending on levels of exposure. These effects are classified in susceptibility and vulnerability, susceptibility is degradation of performance due to Electromagnetic Interference which is high power microwave in this case. When this degradation is sufficient to cause failure of mission, this is classified as vulnerability. Different complex interactions take place after microwave energy reaches the target. Energy coupling to the target can take place through front door coupling or back door coupling [1].

**Front Door Coupling:** When coupling of electromagnetic energy to target takes place through the paths which are created intentionally like antennas and sensors. In this case it becomes difficult to shield against microwave radiation without losing or severely degrading the functionality.

**Back Door Coupling:** This type of coupling takes place through unintended paths, like apertures and imperfections in the system. These apertures can be either intentional or unintentional, intentional apertures may be like holes for drainage and ventilation. Unintentional apertures may be at shield joints.

Estimation of microwave power coupled to electronics can be done using effective cross section area multiplied by the incident microwave power density. While estimating the coupling of microwave power polarization of incident field also plays an important role and it should be taken into account during estimations. Any structure for which estimation of power is to be done, it has to be divided in dipole, loop and transmission line antennas. For these simple structures effective cross section areas known already.

## 21.3. Coupling Mechanism for electronics

Coupling of microwave power can take place through different mechanisms. Rectification, inter modulation, latch-up and thermal damage are the most important mechanism through which disruption of electronics takes place.

In **rectification**, unintended signal propagates through legitimate paths for signal and rectification of signal takes place in victim amplifier, digital circuits etc. These signals can be at times further enhanced by parasitic elements present in the circuits. Rectification is the most prominent coupling mechanism for microwave power.

In case of **intermodulation**, mixing of unintended frequency $f_2$ takes place with intended frequency $f_1$ in the circuit due to nonlinearities present in the victim circuit. New intermodulation products of different orders are generated.

**Latchup** is a phenomenon which is very commonly observed in CMOS circuits. Latchup state is caused due to formation of unintentional parasitic transistor. Here an inadvertent SCR pnpn or npnp is formed, when this switch gets triggered, the device gets disabled. In electronic circuits latching results in operational upsets/ hanging of circuits. If latchup continues for longer time, this can cause burn out in electronic circuits.

**Thermal Damage Process** is a failure mechanism for semiconductor circuits under short pulse exposure. Thermal breakdown is a result of heating in junction region, in this mechanism device gets irreversibly damaged. For pulse widths in the range of 100 ns to 100 μs, the damage threshold power, $P_D$ is proportional to square root of pulse width. For pulses with <100 ns pulse width, thermal process causing device damage is adiabatic in nature. Adiabatic process means, damage occurs before removal of absorbed heat from junction region. Consequently, the energy available to cause damage is proportional to $p_D\tau$. And for long stress pulses (>100 μs), threshold power is no more a function of pulse width, this is classified as constant power region.

Combining all three of the foregoing failure mechanisms into a single relationship yields following equation,

$$\frac{P_D}{A_J} \approx K'\sqrt{A_J}\ \tau^{-1} + K\tau^{-1/2} + \frac{K''}{\sqrt{A_J}}\tau^0 \tag{21.5}$$

Where the proportionality constants are device characteristic, Where $A_J$ is the junction area, τ is pulse width and *K, K', K''* are the proportionality constants. Three regions for microwave power with respect to pulse width are indicated in Figure 21.1 [1, 3].

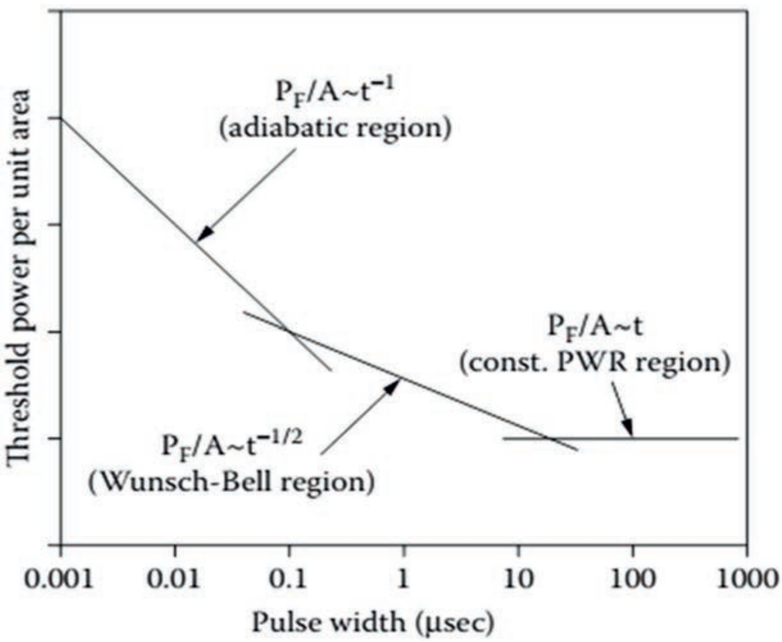


Figure 21.1. Power Density for burn out vs. pulse width [1].

### 21.3.1. Damage Threshold for Semiconductor Devices

Study of damage thresholds for different type of semiconductor devices was done by Antinone and Ng. Results of their experiments revealed that at few GHz of frequencies 100 W power is sufficient for damage in semiconductor devices. As per the dependence on pulse width explained in previous section, for 100 ns pulse width this power requirement increases to 320 W. Table 21.4 summarizes the results for damage threshold for 1 µs rectangular pulse [1, 10].

Table 21.4. Damage Threshold for different type of semiconductor devices [10].

| **Device Name** | **Damage threshold power range for 1 µs rectangular pulse** |
|---|---|
| High Power Transistors | 200 W to 160 kW |
| Silicon Controlled Rectifiers | 130 W to 13 kW |
| Germanium Transistors | 20 W to 6 kW |
| Switching Transistors | 20 W to 300 W |
| Low Power Transistors | 7 W to 2 kW |
| Rectifier Diodes | 600 W to 25 kW |
| Switch Diodes | 25 W to 1 kW |
| Point Contact Diodes | 0.8 W 100 W |
| Microwave Diodes | 0.5 W to 20 W |
| Integrated Circuits | 0.8 W to 25 W |

### 21.3.2. HPM Vulnerability of Digital Circuits and Personal Computers

Modern day digital circuit are having trend of more and more miniaturization, these devices using bipolar transistors, MOS/CMOS circuits are highly vulnerable to HPM radiation from IEMI sources. With decrease in device dimensions and logic levels, susceptibility of modern devices to HPM is increasing. As far as the comparison of analog and digital devices is concerned; it has been observed that upset threshold required for disturbance in digital devices is slightly higher than that for an analog device. Damage threshold for electronic devices/circuits is much higher than upset thresholds. In terms of damage threshold digital devices are slightly inferior to analog devices. Microcontroller circuits of different families have been tested at APPD, BARC with frequencies in 4 GHz range and vulnerability threshold of 89C2051 microcontroller circuit is found to be in the range of 10 kV/m.

Vulnerability of personal computers is a function of frequency. A general trend in reported literature world over has been increase in vulnerability threshold with increase in frequency. A possible reason which can be attributed for this is that at lower frequencies systems are relatively open and pickups are dominated by lots of wires, this kind of effect is observed at frequencies below 1 GHz. Further moving to higher frequencies coupling through apertures and slots takes a prominent role. In general, microwave power with same frequency band as operational clock frequencies of computer is highly effective against computer systems. However, modern day computers are harder to penetrate compared to the older ones. Probably the reason for this possible trend is build quality getting better with time. Vulnerability thresholds for different class of PCs reported in literature are shown in Figure 21.2, testing of

Pentium IV 2000 MHz PC was carried out at APPD, BARC results found were quite in line with literature having a vulnerability threshold of 3.5 kV/m at 3.2 GHz frequency as indicated in Figure 21.2.

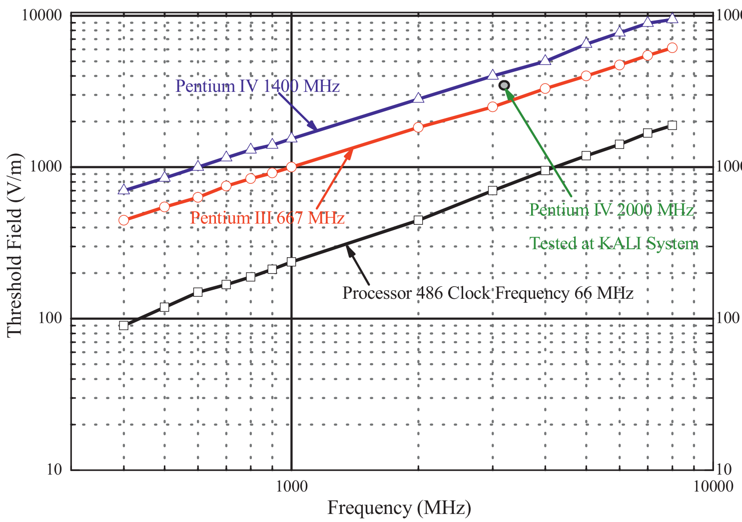


Figure 21.2. Results of testing of different class of PCs from literature.

## 21.4. Stress Quantification

For comparison of different effects of microwaves on circuits or living beings, it is important to quantify the level of effect caused my microwaves. This quantification varies from case to case depending on which metric plays an important role for device performance or behaviour of living beings. Like in dielectric breakdown and arc over effects peak induced voltage plays an important role. For a capacitive termination integral of current function may play an important role. In case of heating effects, it is a function of induced energy in the circuit, while operational upset at times may be a function of peak voltage. Depending on all these factors, following are quantifiers for stress caused due to microwaves:

1. Time domain peak, $\underset{0<t<\infty}{peak}|x(t)|$
2. Total signal energy, $\int_0^\infty |x(t)|^2 dt$
3. Peak signal power, $\underset{0<t<\infty}{peak}|x(t)|^2$
4. Peak time rate of change, $\underset{0<t<\infty}{peak}\left|\frac{d}{dt}x(t)\right|$
5. Peak time integral of the pulse, peak $\int_0^\infty x(t)dt$

Out of these quantifiers as discussed earlier, relevant one is chosen in different scenarios.

## 21.5. Common Exposure Levels from RF Sources

Microwave emission power levels from some commonly encountered RF sources are shown in table 21.5. Microwave power is radiated into atmosphere from these sources due to some leakage which is inadvertently present in case of microwave oven, diathermy equipment, dielectric furnace. In case of handheld transceivers power is required for their functionality [3].

Table 21.5. Emission from Common RF Sources.

| Type of Microwave Source | Microwave Power Exposure Level | Frequency of Operation |
|---|---|---|
| Microwave Oven | $<5$ mW/cm$^2$ | 2.45 GHz |
| Microwave Diathermy | $<10$ mW/cm$^2$ | 2.45 GHz |
| Short Wave Diathermy | $>10$ mW/cm$^2$ | 27.12 MHz |
| Dielectric Furnace | $>10$ mW/cm$^2$ | 20-70 MHz |
| Hand Held Transceivers | $>10$ mW/cm$^2$ | 27.12 MHz, 150 MHz |

## 21.6. Microwave Safety from HPM Systems

General safety standard for microwaves/radio frequency has been discussed in section 21.2.3. For high power microwaves, requirements are more specific which are discussed in this section. Microwave hazards due to HPM can be further classified in biological hazards for people, hazards to the ordnance and hazards to fuel. These three hazards of electromagnetic radiation are abbreviated as HERP, HERO, and HERF. Hazards for the ordnance become a big cause for concern when there are chances of electro-explosive devices (EED) to be initiated. Hazards to fuel can be caused when there is a potential for spark ignition due to high power microwave.

In terms of biological effects, hearing effects are the one observed at lowest power levels. For a 10 µs pulse, microwave energy of the level of 10 µJ/g absorbed in human head results in acoustic response. For short pulse high power microwave pulses, little is known for biological effects on humans and still it is a part of experimentation [1, 8].

### A. HERP

Peak power limits for these types of systems are still not very well defined. Peak power level of 5 W/cm$^2$ can be considered as safe in general. In practice HPM facilities in general use screen/anechoic rooms for operating personnel and attenuate below measurable levels.

Table 21.6. Safety Guidelines for people in controlled areas [8].

| Frequency Band (MHz) | Microwave Power Density | Averaging time (Seconds) |
|---|---|---|
| 300-3000 | 1-10 mW/cm$^2$ | 360 |
| 3000-15000 | 10 mW/cm$^2$ | 360 |
| 15000-300000 | 10 mW/cm$^2$ | 360-9.9 |

**B. HERO**

These are further subdivided in HERO 1 and HERO 2. HERO 1 is for fully assembled ordnance in normal operation and HERO 2 is for bare EEDs. These levels at different frequencies are further listed in table 21.7.

Table 21.7. Safety Guidelines for ordnance.

| (HERO 2) | |
|---|---|
| Frequency of Operation | Microwave Power Density |
| 20 MHz-20 GHz | $10^{-4}$ to 10 mW/cm$^2$(Varies Linearly) |
| 20 GHz- 100 GHz | 10 mW/cm$^2$ |
| (HERO 1) | |
| Frequency of Operation | Microwave Power Density |
| 10 MHz-2 GHz | $2\times10^{-3}$ to $2\times10^{-1}$ mW/cm$^2$ (Varies Linearly) |
| 2 GHz-100 GHz | $2\times10^{-1}$ to 500 mW/cm2 (Varies Linearly) |

**C. HERF**

HERF are important from perspective of inadvertent fuel ignitions caused due to microwave radiations. A voltage gradient below 50 kV/cm is considered safe for this aspect [1].

## 21.7. Summary

This chapter discusses different type of microwave effects like biological effects, effects on electronics, dielectric heating with an introduction to fundamental aspects. After this, specific focus has been kept on high power microwaves. Different safety standards for microwave exposure limits are also described along with available standards for high power microwave effects. Classification of hazards due to electromagnetic radiation is also given in this chapter.

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