The science of magnetism began with Pierre de Maricot who, around 1269, identified the north and south poles of a magnet. Later John Mitchell showed that magnetic attraction varied inversely with the square of the distance between magnetic poles. Electricity began with Stephen Gray, but it was Jean-Theophile Desaguliers who showed that there are two types of materials - namely conductors and insulators. The relation between electricity and magnetism became apparent in 1819, when Christian Oersted observed that a magnetic needle oriented itself perpendicular to a wire carrying electric current. Later, in 1895 Andre Marie Ampere created a new science based on the work of Oersted. He elucidated the laws that governed the production of magnetic field by electric current and determined the forces acting between two conductors carrying current. In 1831, Michael Faraday demonstrated the existence of an induced current in a circuit placed in an alternating magnetic field. He also introduced the concept of a dielectric, defined as a medium in which electric induction can take place. The discovery of Maxwell that light, by its very nature, was electromagnetic was the starting point for the evolution of the concept of an electromagnetic spectrum that extends from dc to cosmic rays.
Chapter 1

The knowledge of interaction between electron beam and electromagnetic field led to the evolution of microwave electronics. With the development of radar, microwave technology flourished tremendously during World War II. Development of devices that could operate in the UHF / microwave bands with high power became the next target. The outcome of this research was the conventional vacuum tube, which at the time seemed to be the best approach. But this device suffered two major problems - the inter electrode capacitance within the vacuum tube and the longer electron transit time. The inter electrode capacitance effectively shorting at higher frequencies and the longer transit time, restricted its use to lower frequencies.

A solution to the transit time problem was proposed in 1920 by German scientists H.Barkhausen and K.Kurz. Their solution was the Barhausen - Kurz oscillator, a special type of vacuum tube that generated high frequency signals. Another solution to these problems was proposed in 1921 by A.W. Hull, who used a magnetic field to influence the flow of electrons. His design was the original magnetron and modifications of his design are still in use today.

The power versus frequency dilemma remained unsolvable for many years. In the mid 1930s, a solution to this problem was proposed by Dr. W.W. Hansen and Dr. A. Heil when they turned the electron transit time into advantage with a mechanism called velocity modulation. Then in 1937, Varian brothers extended Dr. Hansen’s work into the development of the klystron vacuum tube. It could be used either as an oscillator or as a power amplifier. With the production of these vacuum tubes, radar finally became a commercial, albeit a military success at microwave frequencies.
Also, this marked the opening of frequencies in the Giga Hertz range to communication engineers.

Military developments in the decades that followed continued to be in radar, while use of microwaves in the commercial sector was limited primarily to telephone companies. By 1960s, microwave communications had replaced 40% of the telephone circuits. Microwave field became vitally important as man reached out to space. The consumer market saw an explosion in the early 1980s with the television broadcast service to the home of satellite TV transmissions. The 1990s saw a continuous evolution of microwave developments particularly in consumer market place.

Microwave frequencies occupy three decades of electromagnetic spectrum (300 MHz to 300 GHz) that lie between VHF radio waves and far infrared. The broad classification of the electromagnetic spectrum is summarized in Table 1.1.

Table 1.1  Broad classification of electromagnetic spectrum

<table>
<thead>
<tr>
<th>Region</th>
<th>Frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio Frequencies</td>
<td>30 – 30 x 10^3 Hz</td>
</tr>
<tr>
<td>Radio Frequencies</td>
<td>3 x 10^3 Hz – 3 x 10^11 Hz</td>
</tr>
<tr>
<td>Infrared</td>
<td>3 x 10^{11} – 4.1 x 10^{14} Hz.</td>
</tr>
<tr>
<td>Visible</td>
<td>4.1 x 10^{14} – 7.5 x 10^{14} Hz</td>
</tr>
<tr>
<td>Ultraviolet</td>
<td>7.5 x 10^{14} – 10^{18} Hz</td>
</tr>
<tr>
<td>X- rays</td>
<td>&gt; 10^{17} Hz</td>
</tr>
<tr>
<td>γ- rays</td>
<td>&gt; 10^{20} Hz</td>
</tr>
<tr>
<td>Cosmic rays</td>
<td>&gt; 10^{21} Hz</td>
</tr>
</tbody>
</table>

Traditionally microwave domain is sub divided into bands which arises from physiological factors like modes of production and the specific properties of radiation. The division of electromagnetic bands is designated in Table 1.2.
Chapter 1

<table>
<thead>
<tr>
<th>Designation</th>
<th>Frequency range in Giga Hertz</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF</td>
<td>0.003 – 0.030</td>
</tr>
<tr>
<td>VHF</td>
<td>0.030 – 0.300</td>
</tr>
<tr>
<td>UHF</td>
<td>0.300 – 1.0</td>
</tr>
<tr>
<td>L band</td>
<td>1.0 – 2.0</td>
</tr>
<tr>
<td>S band</td>
<td>2.0 – 4.0</td>
</tr>
<tr>
<td>C band</td>
<td>4.0 – 8.0</td>
</tr>
<tr>
<td>X band</td>
<td>8.0 – 12.0</td>
</tr>
<tr>
<td>Ku band</td>
<td>12.0 – 18.0</td>
</tr>
<tr>
<td>K band</td>
<td>18.0 – 27.0</td>
</tr>
<tr>
<td>Ka band</td>
<td>27.0 – 40.0</td>
</tr>
<tr>
<td>Millimeter</td>
<td>40.0 – 300.0</td>
</tr>
<tr>
<td>Sub millimeter</td>
<td>&gt; 300.0</td>
</tr>
</tbody>
</table>

Table 1.2. Various bands in the microwave domain

Microwave radiation obeys the laws of electromagnetism. Electromagnetic wave is a propagation phenomenon which requires no material support but only involves electric and magnetic fields, each of which is a function of time. Wavelengths at microwave frequencies are of the same order of magnitude as the dimensions of the circuit devices, and the time of propagation of electrical effects from one part of the circuit to the other is comparable to the period of oscillating currents and charges. Hence conventional circuit concepts of currents and voltages are replaced by field concepts.

Applications of microwaves can be mainly classified into two domains: information and power. Information domain deals with applications in the field of radar and communications. Power domain includes industrial, scientific and medical (ISM) applications. A chart of microwave applications is shown in Figure 1.1.
1.1 Industrial Scientific and Medical Applications

Microwaves do not provide universal solution to all the problems, but should be considered whenever all other processes fail to solve an industrial problem, in which case the advantages of microwaves become unique.

![Microwave Applications Diagram]

Figure 1.1 Classification chart of the applications of microwaves

Some of the advantages of microwaves are

- Speed of heating, better efficiency, savings in space and man power
- Ease of operation, instantaneous on and off operations.
- Ease of adaptation to existing on-line operations, possible combination with other thermal processes.
- No energy loss by radiation, improved efficiency and working conditions, possibility of eliminating the need for temperature control of the environment
• Better thermal efficiency compared with traditional processes and improved quality.

The frequencies employed for these applications are 434, 915 and 2450 MHz and are called the Industrial Scientific and Medical Applications (ISM) band.

1.1.1 Industrial Applications

Many industrial processes involve one or more stages of product drying, which is often very expensive. Microwaves offer the most viable alternative in terms of energy efficiency. Microwave is used for drying humid materials, which occur in physiochemical forms (e.g., pastes, colloids, suspensions and porous solids containing absorbed liquid) [1]. In printing industry, for superior and well-defined quality results, microwave heating is adopted as it involves no risk of darkening or cracking of paper and no need of high temperature protection [2, 3]. Microwaves can also help in the drying of paper coatings that consist of a very thin layer of mineral particulate. Microwave drying tests on binding agents have demonstrated improved drying efficiency and better coating cohesion [4]. In leather industry microwave is used for the treatment of leather in steam heated dryer under vacuum as it results in high, uniform distribution of humidity thereby avoiding over drying and re-humidification [5]. Microwave drying is employed in textile industry for the treatment of tufts and yarns, and for dyeing and finishing [6]. Microwave is used for the processing of cardboard and paper bags, plywood, plaster, concrete and ceramics, photographic films and magnetic tapes [1]. Microwave treatment of wood avoids the creation of internal strains, ensures uniformity and controls insect attacks [7]. Microwave drying is recommended for drying polymers as it produces no changes in the molecular weights and hence no
damage to the product [8]. Microwaves find application in pharmaceutical industry for the drying of granules [1]. The use of microwave for vulcanization of rubber provides excellent results in terms of efficiency, reliability and adaptability to industrial environment [9, 10]. Microwaves are widely used to reticulate thermosetting resins and to polymerize plastic materials [1]. Large scale industrial applications of microwaves include dewaxing casting moulds [11], pyrolysis of shale oil [12], gasification of coal [13], liquefaction of heavy oil prior to pumping [14], hardening of foundry mouldings [11], fast setting of concrete [15] and sintering of ferrites and ceramics [16]. In nuclear waste treatment, microwaves are being used to solidify droplets of radioactive wastes [17]. The contribution of microwaves in food industry includes cooking poultry, bacon, meat loaves, preparation of sprats, frying of fritters and doughnuts, baking of bread and reheating of prepared meals. Microwave cooking is superior in terms of speed, hygiene, nutrition and in sensory perception [18, 19]. Another successful application of microwaves in food industry lies in thawing and tempering [20, 21]. Microwaves can be used for food preservation by performing enzymatic inactivation, sterilization and pasteurization [22 - 24]. It can also be used for germination of dormant grains, disinfestations of stored cereals and in the making of wine [1].

Applications of microwaves in industry are attributed to the fact that microwave technology offers dust free operation, uniform drying, no accidental burns, no water pockets, energy saving, no environmental heating and prevention of over drying. The use of microwaves in industry has led to 50% improvement in productivity. More over the flexibility of the technique, precision and control, and the ease with which the whole
installation can be supervised, make microwave technology an attractive option for industrial applications than the conventional methods.

1.1.2 Scientific applications
Microwave is successfully used to determine basic semiconductor parameters such as resistivity [25], mobility of charge carriers [26], plasma density measurement [27], atmospheric absorption measurements [28] and ground penetrating radar studies [29]. It is also used as alternating voltage to accelerate electrons in linear accelerator, cyclotron [30], and synchotron [31].

Material characterization [32-34] is another important scientific application of microwaves. The dielectric parameters over a wide range of temperatures on low loss dielectrics are needed to assess their suitability for use in telecommunications, dielectric waveguides, lenses, radomes, dielectric resonators and microwave integrated circuit substrates. Knowledge of the dielectric properties of biological materials is needed to estimate the electrical response of these materials when exposed to microwaves and is thus important in the development of phantoms and coupling media for biomedical applications.

A part of this thesis deals with the identification of suitable materials to be used as phantoms and coupling media for microwave breast imaging.

1.1.3. Medical applications
Microwave technology makes important contributions to both therapeutic and diagnostic medicine. A number of medical devices that use microwaves are in clinical use today [35, 36]. All these devices depend on the ability of microwaves to deeply penetrate into living tissues. The depth to which microwaves can penetrate tissues is primarily a function of the
Introduction
dielectric property of the tissues and of the frequency of the microwaves. When microwaves penetrate into the tissues, they give up energy to the tissues. Thus, microwaves can be used to non-invasively produce hyperthermia, particularly in cutaneous and subcutaneous cancer sites, and in sites that are accessible via natural openings of the body [37]. This most promising therapeutic medical application of microwave seems to have no side effects and continues to be effective as the body does not get accustomed to it. Also it produces minimum discomfort for the patients. As the energy of photons in the microwave region is small, harmful ionization effects are avoided. The results are remarkable when microwave technology is combined with radiotherapy and chemotherapy. Microwave hyperthermia is also effective in relieving neurologic or arthritic pain [38] and for the treatment of prostate cancer [39]. Microwaves can be used for rapid re-warming after accidental hyperthermia or heart surgery. It is reported that high power microwave pulses can enhance the ability of certain chemotherapeutic agents to enter malignant cells. Since microwaves pulses, unlike dc pulses, can non-invasively deeply penetrate the tissues, poration with microwave pulses offers the possibility of non-invasively treating more deep - seated malignancies than is possible with dc pulses [37]. Microwaves also find application in diathermy for mild orthopedic heating [40], microwave ablation [41], microwave assisted balloon angioplasty [42]. It is reported that microwaves are effective in tissue healing and rapid fixation of brain cells [37].

Microwave imaging is another new technology which has potential applications in the field of diagnostic medicine [43]. The basic motivation for this is improved physiologic and pathophysiologic correlation, especially in soft tissues. This expectation is based on the molecular
(dielectric) rather than atomic (density) based interactions of the radiation with the target when compared with X-ray imagery [44]. Due to the improved dielectric contrast, better tissue characterization too is possible. Microwaves can be used effectively for the detection of biological anomalies like tumor at an early curable stage itself.

1.2 Various Imaging techniques

Imaging an object, invisible to naked eyes, is an important quest of scientists. All systems for internal body imaging are based on the differentiation of tissue properties. The various imaging techniques are given below.

1.2.1 X-ray

The standard method of imaging human body is X-ray tomography. An X-ray picture is a shadow cast on a photographic film by denser media that are more opaque to X-rays compared with less dense media. Developing three dimensional pictures out of a series of shadows cast by X-rays is called as X-ray tomography which later developed as Computer – Aided Tomography. In X-ray tomography, a tissue is differentiated based on density. However in most cases, tissue density does not depend on tissue physiological state. Important tissue characteristics such as temperature, blood content, blood oxygenation and ischemia cannot be differentiated by X-ray tomography. For soft tissues like human breast, X-ray cannot image the breast anomalies, as there is no significant variation in density between normal and malignant breast tissues, and has proven to be insensitive to the presence of lesions in the breast. Many a times X-ray reported high false positive rates and high false negative rates [45, 46].
1.2.2 Magnetic Resonance Imaging (MRI)

MRI makes use of the fact that spin echoes of protons have different resonant frequencies depending on the ambient static magnetic field [47]. The body is immersed in a static magnetic field that has a linear gradient in a three-dimensional space. The stronger the magnetic field the higher will be the resonant frequency of the proton spin and louder will be the gradient noise. Even though MRI is a non-ionizing technique, it has many disadvantages. MRI cannot be used for patients having implants, and is claustrophobic. The MRI machine makes tremendous amount of noise, which creates fear in patients. Also, patient should lie still for a long duration of time. Even a slight movement of the part being scanned can cause much distorted images.

1.2.3 Ultrasound imaging

Ultrasound is widely used as it is non-hazardous and can outline some organs which are not successfully imaged by X-rays. Ultrasound images are functions of the propagation velocity of sound waves in the medium. The ultrasound waves diffract around objects instead of travelling in straight lines [48]. Also, multiple scattering effects take place when these waves enter an object. In ultrasound imaging, the effects of diffraction and multiple scattering are not taken into account for image reconstruction and hence image distortion arises.

1.2.4 Optical imaging

Infrared signals have shorter wavelengths than microwaves and therefore have less penetration power. This limits the application of optical imaging to non-invasively image internal body parts [49]. Microwaves have wavelengths of the order of centimeters and so is its penetration strength.
Also, biological tissues are more translucent to microwaves than to infrared signals [49].

1.2.5 Microwave imaging

Microwave images are maps of the electrical property distributions in the body [43]. The electrical properties of various tissues may be related to their physiological state. Cancer detection with microwave imaging is based on this contrast of electrical properties. Tissue dielectric properties in the microwave region depend upon molecular constituents, ion concentration, mobility, concentration of free water & bound water and tissue temperature [50].

The motivation for developing a microwave imaging technique for detecting breast cancer is the significant contrast in dielectric properties of normal and malignant breast tissues at microwave frequencies [51, 52]. Furthermore, microwave attenuation in normal breast tissue is low enough to make signal propagation feasible even through large breast volumes. In addition, microwave technology is non-invasive, non-ionizing and eliminates uncomfortable breast compression. The small size and physical accessibility of the breast compared to other internal organs is also an added advantage.

As application of microwave imaging for breast cancer detection is the research area of this thesis, the technique is discussed in detail below.

1.3. Microwaves for Breast Cancer Detection

“Early detection is the best protection” is the philosophy that drives breast cancer screening programs. An integral component of these programs is X-ray mammography which is X-ray imaging of compressed breast. However, the X-ray mammography suffers many limitations like, missing of 15% of breast cancer, difficulty in imaging women with dense breasts and
production of in-conclusive results [45, 46]. Diagnosis often involves waiting for further imaging or biopsies. These limitations of X-ray mammography provide clear motivation for the development of a complementary breast imaging tool to assist in detection and diagnosis. An ideal breast screening tool should have low health risk, be sensitive to tumors, detect breast cancer at a curable stage, be non-invasive and simple to perform, be cost effective and widely available, involve minimum discomfort, and provide easy to interpret and consistent results [51,52].

For reliable detection of small malignant tumors, a significant and consistent contrast between malignant and normal breast tissues is required. At microwave frequencies the sensitivity, specificity and the ability to detect small tumors is the dielectric contrast between normal and malignant breast tissues. Malignant breast tissues exhibit considerable increase in bound water content compared to the normal tissues and hence a high value of dielectric constant [50].

There are three methods of microwave breast imaging. They are passive, hybrid and active approaches.

1.3.1 Passive Microwave Imaging
The principle of operation relies on increased tumor temperature compared with healthy breast tissues, when exposed to microwaves. This method incorporates radiometers to measure temperature differences in the breast. Images display the temperature measured over a quadrant of the breast [53]. For diagnosis, images of the suspicious lesion and that of the corresponding area of the other breast are compared. Clinical results obtained with the French system ONCOSCAN suggest that microwave radiometry has the potential to assist in the diagnosis of suspicious areas on X-ray mammograms.
1.3.2 Hybrid Microwave Imaging

Hybrid approach, specifically microwave induced acoustic imaging uses microwaves to illuminate the breast. Due to higher conductivity of malignant breast tissue, more energy is deposited in tumors resulting in selective heating of these lesions. The tumors expand and generate pressure waves, which are detected by ultrasound transducers. Two methods of image reconstruction have been proposed, namely computed thermo-acoustic tomography (CTT) [54] and scanning thermo-acoustic tomography (STT) [55]. In CTT, the breast is placed in a water bath and illuminated at 434 MHz with a wave guide. Pulses of 0.5μs are used to generate ultrasound waves in the medical region. Ultrasound transducers are arranged on a bowl, and data is recorded as this bowl rotates through 360°. Image reconstruction uses filtered back propagation algorithms adapted from X-ray computed tomography. With STT approach, image reconstruction is simplified by employing focused transducers to record ultrasound waves. Here the object is illuminated by short duration pulses from a wave guide antenna. Ultrasound transducers record the signals transmitted through the object. The sample is scanned along the axis perpendicular to the transducer, time domain signals are recorded at a number of locations and the collection of signals is displayed as an image. By using focused transducer, this approach avoids complex image reconstruction algorithms.

1.3.3 Active Microwave Imaging

Two classifications of active microwave imaging are discussed here.

1.3.3.1 Confocal Microwave Technique

Confocal Microwave Technique (CMT) uses backscatter methods to infer the locations of significant microwave scatterers [56, 57]. The breast is
illuminated with a wide band pulse from a number of antenna locations and the same antenna collects the backscattered signals. The relative arrival times and amplitudes of the backscattered signal provide information to determine the scatterer location. This approach only identifies the presence and location of strong scatterers in the breast rather than completely reconstructing the dielectric properties profile.

1.3.3.2 Microwave Tomographic Imaging

Microwave tomographic imaging poses an inverse scattering problem where the breast is illuminated by a microwave transmitter, and scattered fields are measured at numerous locations [58, 59]. The shape of the object and spatial distribution of the complex permittivity are obtained from the transmitted and the collected scattered fields. Due to the relationship between the object dimensions, discontinuity, separation and contrast in properties of inhomogeneities compared to wavelength, the wave undergoes multiple scattering within the object. This results in a non-linear relationship between the measured scattered fields and the object function. In general, inverse scattering approach (especially for whole body imaging) suffers from non-uniqueness and multiple wrappings of the scattered field phases. However with smaller geometries, as in the case of breast imaging, these concerns are minimal.

1.4 Brief sketch of the present study

Development of active microwave imaging techniques for detection of breast cancer is presented in this thesis. The thesis is organized in different chapters as given below.
Chapter 2 explains in brief the dielectric behavior of biological materials and the dielectric spectrum of biological tissues. Various polarization effects are discussed. Cavity perturbation techniques used for the measurement of dielectric parameters are also mentioned.

Chapter 3 gives the design of coplanar strip line fed bowtie antenna for microwave imaging, and optimization of the antenna dimensions. Experimental studies on the radiation characteristics of the antenna are discussed. Theoretical validation of the experimental observation is performed using finite difference time domain analysis.

Chapter 4 discusses the development of suitable phantoms and coupling media for microwave breast imaging. The dielectric constant and conductivity studies of the materials in different concentrations are performed using cavity perturbation technique. The results are compared with the available literature data on normal and malignant breast tissues. The performance of the antenna when immersed in the coupling medium is also studied.

Chapter 5 deals with two dimensional microwave tomographic imaging technique. Both breast phantoms and breast tissues are subjected to the study. Two dimensional images are reconstructed from the experimentally collected scattered fields using distorted Born iterative method and profiles of their dielectric constants are studied.

Chapter 6 deals with the confocal microwave technique for the detection of biological anomalies, using breast phantoms and breast tissues.
Experimentally collected backscattered waveforms are analyzed in the time domain and regions of dielectric contrast are determined. Experimental results are substantiated by finite difference time domain analysis.

The conclusions drawn from the studies and further extensions of the work are discussed in Chapter 7.

Related research works carried out by the author during this period are included in Appendices A & B.

Appendix A deals with 2-D microwave tomographic imaging of biological objects like calf femur, chicken thigh and wood sample, and wax cylinder with water inclusion.

Appendix B deals with the dielectric studies of mixture of carbon black powder, graphite powder and polyvinyl acetate based adhesive in definite proportions. The feasibility of using this material as phantom for low water content biological tissues and as absorbing material for microwave tomographic imaging is analyzed.

In Appendix C, the details of the driver circuit used to activate the stepper motor of the experimental set up for data acquisition is discussed.
1.5. References


