Effect of Dielectric and Polymer Materials on Various Parameters of Parabolic Antenna in C and X Band

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<u>Certificate</u>

This is to certify that the dissertation entitled "***Effect of Dielectric and Polymer Materials on Various Parameters of Parabolic Antenna in C and X Band***" submitted by **Fayaz Ahmad Wani**, in partial fulfillment for the award of the degree of **Master of Philosophy** in **Physics**, is the original research work carried out by him under my supervision and guidance. It is further certified that the dissertation has not been submitted for the award of M. Phil or any other degree to this University or any other University. The scholar has attended the department for statutory period as required under rules.

Dr. Gowhar Bashir   **Prof. Sheikh Javid Ahmad**

(*Supervisor*)   (*Head of the Department*)

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May the Almighty Allah give them a happy life and bless them with good health (Amin!).

Fayaz Ahmad Wani

Dedicated

To

My parents

Always been an Inspiration

Preface

The work presented in this thesis was carried out at the Electronic Research Laboratory, Department of Physics, University of Kashmir, Srinagar. Due to the large applicability of dielectric and polymer materials in communication, it was thought with an aim of this thesis to investigate how to improve the basic parameters of different antennas.

The thesis is divided into six chapters. First chapter gives an introduction to Antennas and basic parameters. Chapter two describes the parabolic antenna and its different types. Chapter three gives brief description of dielectric materials and its properties. Chapter four describes the polymers and its types, applications and processing of polymers and its properties. Chapter five describes the effect of dielectric and polymer material on various antennas. Chapter six gives summary and future plan of the present work. Refer-ences to the literature are mentioned at the end of the thesis.

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Chapter 1

Introduction to antennas and basic parameters

1.1 Introduction

Antennas are devices used for radiating and receiving electromagnetic waves. These are ubiquitous in military surveillance applications and antennas are commonly used in a large number of commercial telecommunication applications like cellular and PCS. Antennas come in a variety of shapes and sizes and in general sophisticated electromagnetic computational techniques are used to design their geometry for specific applications.

In addition, large bandwidth, tunability and mechanical flexibility of the antennas are all desirable properties. These factors place rather stringent requirements on the material parameters as well as geometry and design of radiation-efficient antennas. The ultimate performance and efficiency of antennas are governed by the intrinsic properties of materials used in fabricating them [1]. It has been observed that gain radiation characteristics for a

standard antenna can be improved by using various dielectric materials [1,2]. The dielectric rod antenna has proved to be useful device in certain specialized application in beacons, arrays, short range communication system where end-fire characteristics with high gain and stable radiation patterns against frequency are desired [6,7]. The gain obtained with well designed dielectric antenna is of the order of rectangular horn antenna & the -3db beam width is much smaller than that of a rectangular horn. Typical values of antenna power gains have been found of the order of 17db & -3db beam widths are less than 20 degrees in X-band (8.5-11.5) GHZ frequencies. At millimeter wave frequencies dielectric rod antennas provide significant performance advantage and are at low cost alternative to free space high gain antenna design such as yagi-uda and horn antennas which are often more difficult to manufacture at these frequencies[11].

1.2   Basic Parameters of Antenna

Some basic parameters affect an antennas performance. The designer must consider these design parameters and should be able to adjust, as needed, during the design process the frequency band of operation, polarization, input impedance, radiation pattern, gain and efficiency. An antenna in transmitting mode has a maximum power acceptance. An antenna in the receiving mode differs in its noise rejection properties. The designer should evaluate and measure all of these parameters using various means.

1.3 Impedance

As electromagnetic waves travel through the different parts of the antenna system, from the source (device) to the feed line to the antenna and finally to free space, they may encounter differences in Impedance at each interface. Depending on the impedance match, some fraction of the waves energy will reflect back to the source, forming a standing wave in the feed line. The ratio of maximum power to minimum power in the wave can be measured and is called the standing wave ratio (SWR). An SWR of 1:1 is ideal. An SWR of 1.5:1 is considered to be marginally acceptable in the low- power application where power loss is more critical, although an SWR as high as 6:1 may still be usable with the right equipment. Minimizing impedance differences at each interface will reduce SWR and maximum power transfer through each part of the system.

The frequency response of an antenna at its port is defined as input impedance (Z_{in}).The input Impedance is the ratio between the voltage and current at the antenna port. Input Impedance is a complex quantity that varies with frequency as $Z_{in}(f) = R_{in}(f) + jX_{in}(f)$, where f is the frequency. The antenna has an input impedance of $Z_{in} = R_a + jX_s$. The real part consists of the radiation resistance (R_r) and the antenna losses (R_l). The input can then be used to determine the reflection coefficient (Γ) and related parameters, such as voltage standing wave ratio (VSWR) and return loss (RL), as a function of frequency as given in [1,2,3,4]

$$\Gamma = \frac{Z_{in} - Z_o}{Z_{in} + Z_o} \tag{1.1}$$

Where Zo is the normalizing impedance of the port. If Z_o is complex, the

reflection coefficient can be modified to be

$$\Gamma = \frac{Z_{in} - Z_o^*}{Z_{in} + Z_o} \tag{1.2}$$

Where Z_o^* is the conjugate of nominal impedance. The VSWR is given as

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma} \tag{1.3}$$

And the return loss is defined as

$$RL = -20 \log \Gamma \tag{1.4}$$

The impedance of the antenna can be adjusted through the design process to be matched with the feed line and have less reflection to the source.

1.4 Bandwidth

The bandwidth is the antenna operating frequency band within which the antenna performs as desired. The bandwidth could be related to the antenna matching band if its radiation patterns do not change within this band. In fact, this is the case for small antennas where a fundamental limit relates bandwidth, size and efficiency. The bandwidth of other antennas might be affected by the radiation patterns characteristics, and the radiation characteristics might change although the matching of the antenna is acceptable. We can define antenna bandwidth in several ways. Ratio bandwidth (BWr) is

$$BW_r = \frac{f_v}{f_l} \tag{1.5}$$

Where f_v and f_l are the upper and lower frequency of the band respectively.

1.5 Radiation Pattern

Radiation patterns are graphical representation of the electromagnetic power distribution in free space. Also, these patterns can be considered to be representatives of the relative field strengths of the field radiated by the antenna [12-15].For the ideal isotropic antenna, this would be a sphere. For a typical dipole, this would be toroid. The Radiation pattern of an antenna is typically represented by a three-dimensional graph. The graph should show sidelobes and backlobes.

1.6 Polarization of the Antenna

The Polarization of an Antenna is the orientation of the electric-field (E-plane) of the radio wave with respect to earths surface and is determined by the physical structure and orientation of the antenna. It has nothing in common with the antenna directionality terms: horizontal, vertical and circular. Thus, a simple straight wire antenna will have one polarization when mounted vertically and a different polarization when mounted horizontally. Electromagnetic wave polarization filters are circuits that can be employed to act directly on the electromagnetic wave to filter out wave energy of an undesired polarization and to pass wave energy of a desired polarization.

Reflections generally affect polarization. For radio waves, the most important reflector is ionosphere- the polarization of signals reflected from it will change unpredictably. For signals reflected by the ionosphere, polarization cannot be relied upon. For line- of sight communications, for which polarization can be relied upon, having the transmitter and receiver use the

same polarization can make a huge difference in signal quality; many tens of dB difference is commonly seen, and this is more than enough to make up the difference between reasonable communication and broken link.

Polarization is the sum of the E-plane orientations over time projected onto an imaginary plane perpendicular to the direction of motion of the radio wave. In the most general case, polarization is elliptical (the projection is oblong), meaning that the polarization of the radio waves emitting from the antenna is varying over time. Two special cases are linear polarization (the ellipse collapses into a line) and circular polarization (in which the ellipse varies maximally). In linear polarization, the antenna compels the electric field of the emitted radio wave to particular orientation. Depending on the orientation of the antenna mounting, the

1.7   Directivity and Gain

The directivity of an antenna has been defined as the ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions. In other words, the directivity of a nonisotropic source is equal to the ratio of its radiation intensity in a given direction, over that of an isotropic source [12-15]:

$$D = \frac{U}{U_i} = \frac{4\pi U}{P_r} \tag{1.6}$$

Where D is the directivity of the antenna; U is the radiation intensity of the antenna; U_i is the radiation intensity of an isotropic source; and P_r is the total power radiated. Sometimes, the direction of the directivity is not specified. In this case, the direction of the maximum radiation intensity is

implied and the maximum directivity is given as

$$D_{max} = \frac{U_{max}}{U_i} = \frac{4\pi U_{max}}{P_r} \qquad (1.7)$$

Where D_{max} is the maximum directivity and Umax is the maximum radiation intensity.

1.8 Gain of antenna

Gain as a parameter measures the directionality of a given antenna. An antenna with low gain emits radiation with about the same power in all directions, where as a high-gain antenna will preferentially radiate in particular direction. Specifically, the gain, directive gain, or power gain of an antenna is defined as the ratio of the intensity (power per unit surface) radiated by the antenna in a given direction at an arbitrary distance divided by the intensity radiated at same distance by a hypothetical isotropic lossless antenna. Since the radiation intensity from a lossless isotropic antenna equals the power into the antenna divided by a solid angle of 4π steradians, we can write the following equation:

$$G = \frac{4\pi U}{P_{in}} \qquad (1.8)$$

Although the gain of an antenna is directly related to its directivity, antenna gain is a measure that takes into account the efficiency of the antenna as well as its directional capabilities. In contrast, directivity is defined as a measure that takes into account only the directional properties of the antenna, and therefore, it is only influenced by the antenna pattern. If, however, we assume an ideal antenna without losses, then antenna gain will

equal directivity as the antenna efficiency factor equals 1 (100% efficiency). In practice, the gain of an antenna is always less than its directivity.

$$
\begin{aligned}
G &= \frac{4\pi U}{P_{in}} \\
&= e_{cd}\frac{4\pi U}{P_r} \\
&= e_{cd}D
\end{aligned}
\tag{1.9}
$$

This gives the relation between antenna gain and directivity, where e_{cd} is the antenna radiation efficiency factor, D the directivity of the antenna, and G the antenna gain. We usually deal with relative gain, which is defined as the power gain ratio in a specific direction of the antenna to the power gain ratio of a reference antenna in the same direction. The input power must be the same for both antennas while performing this type of measurement. The reference antenna is usually a dipole, horn, or any other of antenna whose power gain is already calculated.

1.9 Antenna Efficiency

Antenna efficiency is the measure of the antennas ability to transmit the input power into radiation [12-15] . Antenna efficiency is the ratio between the radiated powers to the input power:

$$
e = \frac{P_r}{P_{in}}
\tag{1.10}
$$

Different types of efficiencies contribute to the total efficiency. The total antenna efficiency is the multiplication of all these efficiencies. Efficiency is affected by the losses within the antenna itself and the reflection due to the

mismatch at the antenna terminal. Efficiency is the ratio of power actually radiated to the power input into the antenna terminals. A dummy load may have an SWR of 1:1 but efficiency of 0, as it absorbs all power and radiates heat but not RF energy, showing that SWR alone is not an effective measure of an antennas efficiency. Radiation in an antenna is caused by radiation resistance, which can only be measured as a part of total resistance, including loss resistance. Loss resistance usually results in heat generation rather than radiation and reduces efficiency. Mathematically, efficiency is calculated as radiation resistance divided by total resistance.

1.10   Basic antenna models

There are many variations of antennas. Below are a few basic models.

The isotropic radiator is a purely theoretical antenna that radiates equally in all directions. It is considered to be a point in space with no dimensions and no mass. This antenna cannot physically exist, but is useful as a theoretical model forcomparison with all other antennas. Most antennas' gains are measured with reference to an isotropic radiator, and are rated in dBi (decibels with respect to an isotropic radiator).

1.10.1   The dipole antenna

A dipole antenna is a radio antenna that can be made of a simple wire, with a center-fed driven element as shown in figure 1.1. It consists of two metal conductors of rod or wire, oriented parallel and collinear with each other (in line with each other), with a small space between them. The simplest

practical antennas from a theoretical point of view. They are used alone as antennas, notably in traditional "rabbit ears" television antennas, and as the driven element in many other types of antennas, such as the Yagi. Dipole antennas were invented by German physicist Heinrich Hertz around 1886 in his pioneering experiments with radio waves. Radio frequency voltage is applied to the antenna at the center, between the two conductors. Dipoles that are much smaller than the wavelength of the signal are called Hertzian, short, or infinitesimal dipoles. These have a very low radiation resistance and a high reactance, making them inefficient, but they are often the only available antennas at very long wavelengths. Dipoles whose length is half the wavelength of the signal are called half-wave dipoles, and are more efficient. In general radio engineering, the term dipole usually means a half-wave dipole (center-fed).
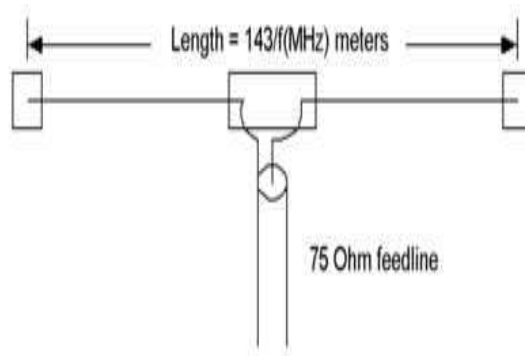
Figure 1.1: Schematic representation of a dipole antenna.

A half-wave dipole is cut to length l for frequency f MHz according to the formula l =143/f where l is in meters or l =468/f where l is in feet. This is because the impedance of the dipole is purely resistive at about this length. The length of the dipole antenna is approximately 95% of half a wavelength

at the speed of light in free space. The exact value depends on the ratio of the wire radius to wavelength, as the reactance of a dipole depends on the ratio of wire radius to wavelength. For thin wires (radius = 0.000001 wavelengths, this is approximately 98.1%, dropping to 91.5% for thick wires (radius = 0.01 wavelengths).

1.10.2   The Yagi-Uda antenna

A basic yagi consists of a certain number of straight elements, each measuring approximately half wave length. The driven or active element of a yagi is the equivalent of a center-fed, half-wave dipole antenna Paralleto the driven element, and approximately 0.2 to 0.5 wave length on either side of it, are straight rods or wires called reflectors and directors, or passive elements altogether. A reflector is placed behind the driven element and is slightly longer than half wavelength; a director is placed in front of the driven element and is slightly shorter than half wavelength. A typical yagi has one reflector and one or more directors. The antenna propagates the electromagnetic field energy in the direction running from the driven element toward the directors, and is most sensitive to incoming electromagnetic field energy in this same direction the more directors a yagi has, the greater the gain. As more directors are added to a yagi, however, it becomes longer.

Figure 1.2 shows the yagi antenna with 6 directors and one reflector. Yagi antennas are used primarily for point-to-point, have a gain from 10 to 20 dBi and a horizontal beam width of 10 to 20 degrees.

Figure 1.2: photograph of a yagi antenna with 6 directors and one reflector.

1.10.3   The horn antenna

A horn antenna or microwave horn is an antenna that consists of a flaring metal waveguide shaped like a horn to direct radio waves in a beam. Horns are widely used as antennas at UHF and microwave frequencies, above 300MHz [18]. They are used as feeders (called feed horns) for larger antenna structures such as parabolic antennas, as standard calibration antennas to measure the gain of other antennas, and as directive antennas for such devices as radar guns, automatic door openers, and microwave radiometers.[19] Their advantages are moderate directivity (gain), low SWR, broad bandwidth, and simple construction and adjustment.[20]

One of the first horn antennas was constructed in 1897 by Indian radio researcher Jagadish Chandra Bose in his pioneering experiments with microwaves.[21][22] In the 1930s the first experimental research (Southworth and Barrow, 1936) and theoretical analysis (Barrow and Chu, 1939) of horns as antennas was done.[23] The development of radar in World War 2 stimulated horn research to design feed horns for radar antennas. The corrugated horn invented by Kay in 1962 has become widely used as a feed horn for

microwave antennas such as satellite dishes and radio telescopes.[23] An advantage of horn antennas is that since they have no resonant elements, they can operate over a wide range of frequencies, a wide bandwidth. The usable bandwidth of horn antennas is typically of the order of 10:1, and can be up to 20:1 (for example allowing it to operate from 1GHz to 20GHz).[18] The input impedance is slowly-varying over this wide frequency range, allowing low VSWR over the bandwidth. The gain of horn antennas ranges up to 25 dBi, with 10 - 20 dBi being typical.[18]

1.10.4 Microstrip antennas

In telecommunication, there are several types of microstrip antennas (also known as printed antennas) the most common of which is the microstrip patch antenna or patch antenna.

A patch antenna is a narrowband, wide-beam antenna fabricated by etching the antenna element pattern in metal trace bonded to an insulating dielectric substrate, such as a printed circuit board, with a continuous metal layer bonded to the opposite side of the substrate which forms a ground plane. Common microstrip antenna shapes are square, rectangular, circular and elliptical, but any continuous shape is possible. Some patch antennas do not use a dielectric substrate and instead made of a metal patch mounted above a ground plane using dielectric spacers; the resulting structure is less rugged but has a wider bandwidth. Because such antennas have a very low profile, are mechanically rugged and can be shaped to conform to the curving skin of a vehicle, they are often mounted on the exterior of aircraft and spacecraft, or are incorporated into mobile radio communications devices.

Microstrip antennas are relatively inexpensive to manufacture and design because of the simple 2-dimensional physical geometry. They are usually employed at UHF and higher frequencies because the size of the antenna is directly tied to the wavelength at the resonant frequency. A single patch antenna provides a maximum directive gain of around 6-9 dBi. It is relatively easy to print an array of patches on a single (large) substrate using lithographic techniques. Patch arrays can provide much higher gains than a single patch at little additional cost; matching and phase adjustment can be performed with printed microstrip feed structures, again in the same operations that form the radiating patches. The ability to create high gain arrays in a low-profile antenna is one reason that patch arrays are common on airplanes and in other military applications. Such an array of patch antennas is an easy way to make a phased array of antennas with dynamic beam forming ability.[24]

An advantage inherent to patch antennas is the ability to have polarization diversity. Patch antennas can easily be designed to have vertical, horizontal, right hand circular (RHCP) or left hand circular (LHCP) polarizations, using multiple feed points, or a single feed point with asymmetric patch structures. [25] This unique property allows patch antennas to be used in many types of communications links that may have varied requirements.

The most commonly employed microstrip antenna is a rectangular patch. The rectangular patch antenna is approximately a one-half wavelength long section of rectangular microstrip transmission line. When air is the antenna substrate, the length of the rectangular microstrip antenna is approximately one-half of a free-space wavelength. As the antenna is loaded with a dielectric

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as its substrate, the length of the antenna decreases as the relative dielectric constant of the substrate increases. The resonant length of the antenna is slightly shorter because of the extended electric "fringing fields" which increase the electrical length of the antenna slightly. An early model of the microstrip antenna is a section of microstrip transmission line with equivalent loads on either end to represent the radiation loss.

The dielectric loading of a microstrip antenna affects both its radiation pattern and impedance bandwidth. As the dielectric constant of the substrate increases, the antenna bandwidth decreases which increases the Q factor of the antenna and therefore decreases the impedance bandwidth. This relationship did not immediately follow when using the transmission line model of the antenna, but is apparent when using the cavity model which was introduced in the late 1970s by Lo et al.[26] The radiation from a rectangular microstrip antenna may be understood as a pair of equivalent slots. These slots act as an array and have the highest directivity when the antenna has an air dielectric and decreases as the antenna is loaded by material with increasing relative dielectric constant.

The half-wave rectangular microstrip antenna has a virtual shorting plane along its center. This may be replaced with a physical shorting plane to create a quarter-wavelength microstrip antenna. This is sometimes called a half-patch. The antenna only has a single radiation edge (equivalent slot) which lowers the directivity/gain of the antenna. The impedance bandwidth is slightly lower than a half-wavelength full patch as the coupling between radiating edges has been eliminated.

Chapter 2

The Parabolic Antenna

2.1 Introduction

Antennas based on parabolic reflectors are the most common type ofdirective antennas when a high gain is required. The main advantage is that they can be made to have gain and directivity as large as required. The main problem or disadvantage is that big dishes are difficult to mount and are likely to have a large windage.The basic property of a perfect parabolic reflector is that it converts a spherical wave radiating from a point source placed at the focus into a plane wave. Conversely, all the energy received by the dish from a distant source is reflected to a single point at the focus of the dish. The position of the focus, or focal length, is given by:

$$f = \frac{D^2}{16 \times c} \tag{2.1}$$

Where D is the dish diameter and c is the depth of the parabola at its Center.The size of the dish is the most important factor since it determines the maximum gain that can be achieved at the given frequency and the

resulting beam width. The gain and beam width obtained are given by:

$$G = \frac{n \times (\pi \times D)^2}{\lambda^2} \tag{2.2}$$

$$BW = \frac{70\lambda}{D} \tag{2.3}$$

Where D is the dish diameter and n is the efficiency. The efficiency is determined mainly by the effectiveness of illumination of the dish by the feed, but also by other factors. Each time the diameter of a dish is doubled, the gain is four times, or 6 dB, greater. If both stations double the size of their dishes, signal strength can be increased of 12 dB, a very substantial gain. An efficiency of 50% can be assumed when hand-building the antenna.

The ratio f/D (focal length/diameter of the dish) is the fundamental factor governing the design of the feed for a dish. The ratio is directly related to the beam width of the feed necessary to illuminate the dish effectively. Two dishes of the same diameter but different focal lengths require different design of feed if both are to be illuminated efficiently.

The value of 0.25 corresponds to the common focal-plane dish in which the focus is in the same plane as the rim of the dish. Dishes up to one meter are usually made from solid material. Aluminium is frequently used for its weight advantage, its durability and good electrical characteristics. Windage increases rapidly with dish size and soon becomes a severe problem. Dishes which have a reflecting surface that uses an open mesh are frequently used. These have a poorer front-to-back ratio, but are safer to use and easier to build. Copper, aluminium, brass, galvanized steel and iron are suitable mesh materials. .

A parabolic antenna is an antenna that uses a parabolic reflector, a curved surface with the cross-sectional shape of a parabola, to direct the radio waves.

Figure 2.1: photograph of a parabolic antenna.

The most common form is shaped like a dish and is popularly called a dish antenna or parabolic dish. .

The main advantage of a parabolic antenna is that it is highly directive; it functions similarly to a searchlight or flashlight reflector to direct the radio waves in a narrow beam, or receive radio waves from one particular direction only. Parabolic antennas have some of the highest gains, that is they can produce the narrowest beam width angles, of any antenna type [27].1 In order to achieve narrow beam widths, the parabolic reflector must be much larger than the wavelength of the radio waves used, so parabolic antennas are used in the high frequency part of the radio spectrum, at UHF and microwave (SHF) frequencies, at which wavelengths are small enough that conveniently sized dishes can be used.

Parabolic antennas are used as high-gain antennas for point-to-point communication, in applications such as microwave relay links that carry telephone and television signals between nearby cities, wireless WAN/LAN links for data communications, satellite and spacecraft communication antennas, and radio telescopes. Their other large use is in radar antennas, which need to

emit a narrow beam of radio, waves to locate objects like ships and airplanes. With the advent of home satellite television dishes, parabolic antennas have become a ubiquitous feature of the modern landscape.
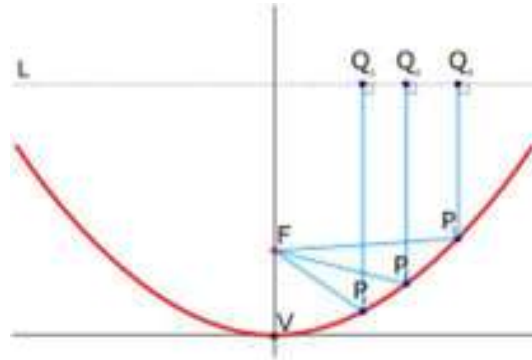
Figure 2.2: Schematic representation of reflection of radio waves by a parabolic antenna.

In a parabolic antenna, incoming parallel radio waves $(Q_1 - Q_3)$ are reflected to a point at the dish's focus (F), where they are received by a small feed antenna. .

2.2 Design of parabolic antenna

The operating principle of a parabolic antenna is that a point source of radio waves at the focal point in front of a paraboloidal reflector of conductive material will be reflected into a collimated plane wave beam along the axis of the reflector. Conversely, an incoming plane wave parallel to the axis will be focused to a point at the focal point.

A typical parabolic antenna consists of a metal parabolic reflector with a small feed antenna suspended in front of the reflector at its focus, pointed

back toward the reflector. The reflector is a metallic surface formed into a paraboloid of revolution and usually truncated in a circular rim that forms the diameter of the antenna. In a transmitting antenna, radio frequency current from a transmitter is supplied through a transmission line cable to the feed antenna, which converts it into radio waves. The radio waves are emitted back toward the dish by the feed antenna and reflect off the dish into a parallel beam. In a receiving antenna the incoming radio waves bounce off the dish and are focussed to a point at the feed antenna, which converts them to electric currents which travel through a transmission line to the receiver.

2.3   Parabolic reflector

The reflector can be of sheet metal, metal screen, or wire grill construction, and it can be either a circular "dish" or various other shapes to create different beam shapes. A metal screen reflects radio waves as well as a solid metal surface as long as the holes are smaller than 1/10 of a wavelength, so screen reflectors are often used to reduce weight and wind loads on the dish. To achieve the maximum gain, it is necessary that the shape of the dish be accurate within a small fraction of a wavelength, to ensure the waves from different parts of the antenna arrive at the focus in phase [citation needed]. Large dishes often require a supporting truss structure behind them to provide the required stiffness.

2.4 Feed antenna

The feed antenna at the reflector's focus is typically a low-gain type such as a half-wave dipole or more often a small horn antenna called a feed horn. In more complex designs, such as the Cassegrain and Gregorian, a secondary reflector is used to direct the energy into the parabolic reflector from a feed antenna located away from the primary focal point. The feed antenna is connected to the associated radio-frequency (RF) transmitting or receiving equipment by means of a coaxial cable transmission line or waveguide.

An advantage of parabolic antennas is that most of the structure of the antenna (all of it except the feed antenna) is no resonant, so it can function over a wide range of frequencies, that is a wide bandwidth. All that is necessary to change the frequency of operation is to replace the feed antenna with one that works at the new frequency. Some parabolic antennas transmit or receive at multiple frequencies by having several feed antennas mounted at the focal point, close together.

2.5 Types of parabolic antennas

Parabolic antennas are distinguished by their shapes:

2.5.1 Paraboloidal or dish

he reflector is shaped like a paraboloid. This is the most common type. It radiates a narrow pencil-shaped beam along the axis of the dish.

2.5.2 Shrouded dish

Sometimes a cylindrical metal shield is attached to the rim of the dish[28]. The shroud shields the antenna from radiation from angles outside the main beam axis, reducing the sidelobes. It is sometimes used to prevent interference in terrestrial microwave links, where several antennas using the same frequency are located close together. The shroud is coated inside with microwave absorbent material. Shrouds can reduce back lobe radiation by 10 dB[28].

2.5.3 Cylindrical

The reflector is curved in only one direction and flat in the other. The radio waves come to a focus not at a point but along a line. The feed is sometimes a dipole antenna located along the focal line. Cylindrical parabolic antennas radiate a fan-shaped beam, narrow in the curved dimension, and wide in the uncurved dimension. The curved ends of the reflector are sometimes capped by flat plates, to prevent radiation out the ends, and this is called a pillbox antenna.

2.5.4 Shaped-beam antennas

Modern parabolic antennas can be designed to produce a beam or beams of a particular shape, rather than just the narrow "pencil" or "fan" beams of the simple dish and cylindrical antennas above [29]. Two techniques are used, often in combination, to control the shape of the beam.

2.5.5 Shaped reflectors

With a single feed antenna, the only option is to alter the shape of the reflector(s). The parabolic reflector can be given a noncircular shape, and/or different curvatures in the horizontal and vertical directions, to alter the shape of the beam. This is often used in radar antennas.

2.5.6 Orange peel" antenna

Used in search radars, this is a long narrow antenna shaped like the letter "C". It radiates a narrow vertical fan shaped beam.

2.6 Arrays of feeds

In order to produce an arbitrary shaped beam, instead of one feed horn an array of feed horns clustered around the focal point can be used. Array-fed antennas are often used on communication satellites, particularly direct broadcast satellites, to create a downlink radiation pattern to cover a particular continent or coverage area. They are often used with secondary reflector antennas such as the Cassegrain. Parabolic antennas are also classified by the type of feed, that is, how the radio waves are supplied to the antenna:[28]

2.6.1 Axial or front feed

This is the most common type of feed, with the feed antenna located in front of the dish at the focus, on the beam axis. A disadvantage of this type is that the feed and its supports block some of the beam, which limits the aperture efficiency to only 55-60% [28].

2.6.2 Off-axis or offset feed

The reflector is an asymmetrical segment of a paraboloid, so the focus, and the feed antenna, is located to one side of the dish. The purpose of this design is to move the feed structure out of the beam path, so it doesn't block the beam. It is widely used in home satellite television dishes, which are small enough that the feed structure would otherwise block a significant percentage of the signal. Offset feed is also used in multiple reflector designs such as the Cassegrain and Gregorian, below.

2.6.3 Cassegrain

In a Cassegrain antenna the feed is located on or behind the dish, and radiates forward, illuminating a convex hyperboloidal secondary reflector at the focus of the dish. The radio waves from the feed reflect back off the secondary reflector to the dish, which forms the outgoing beam. An advantage of this configuration is that the feed, with its waveguides and "front end" electronics does not have to be suspended in front of the dish, so it is used for antennas with complicated or bulky feeds, such as large satellite communication antennas and radio telescopes. Aperture efficiency is on the order of 65 - 70% [28].

2.6.4 Gregorian

Similar to the Cassegrain design except that the secondary reflector is concave, (ellipsoidal) in shape. Aperture efficiency over 70% can be achieved[28].

2.7 Main types of parabolic antenna feeds

The main types of parabolic antenna feeds are shown in figure 2.3.
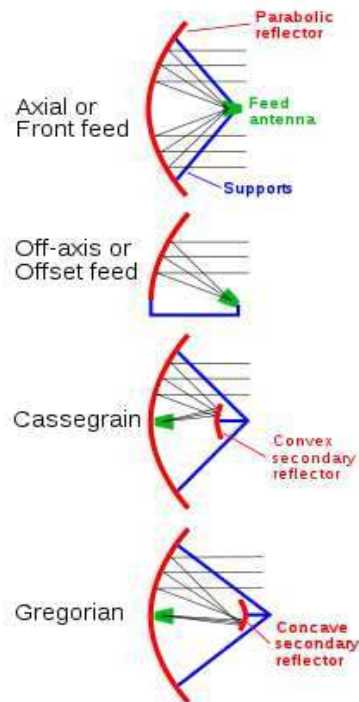
Figure 2.3: Schematic representation of different types of parabolic antenna feeds.

2.8 Gain of parabolic antenna

The directive qualities of an antenna are measured by a dimensionless parameter called its gain, which is the ratio of the power received by the antenna from a source along its beam axis to the power received by a hypothetical isotropic antenna. The gain of a parabolic antenna is [31]:

$$G = \frac{4\pi A}{\lambda^2} e_A = \frac{\pi^2 d^2}{\lambda^2} e_A \qquad (2.4)$$

Where: A is the area of the antenna aperture, i.e., the mouth of the parabolic reflector; d is the diameter of the parabolic reflector; λ is the wavelength of the radio waves.

e_A is a dimensionless parameter between 0 and 1 called the aperture efficiency. The aperture efficiency of typical parabolic antennas is 0.55 to 0.70. It can be seen that, as with any aperture antenna, the larger the aperture is, compared to the wavelength, the higher the gain. The gain increases with the square of the ratio of aperture width to wavelength, so large parabolic antennas, such as those used for spacecraft communication and radio telescopes, can have extremely high gain. Applying the above formula to the 25-meter-diameter antennas often used in radio telescope arrays and satellite ground antennas at a wavelength of 21 cm (1.42 GHz, a common radio astronomy frequency), yields an approximate maximum gain of 140,000 times or about 50 dBi (decibels above the isotropic level).

Aperture efficiency e_A is a catchall variable which accounts for various losses that reduce the gain of the antenna from the maximum that could be achieved with the given aperture[32].

2.9 Beam width

The angular width of the beam radiated by high-gain antennas is measured by the half-power beam width (HPBW), which is the angular separation between the points on the antenna radiation pattern at which the power drops to one-half (-3 dB) its maximum value. For parabolic antennas, the HPBW θ is given by [30 ,32]:

$$\theta = \frac{k\lambda}{d} \tag{2.5}$$

Where k is a factor which varies slightly depending on the shape of the reflector and the feed illumination pattern. For a "typical" parabolic antenna k = 70 when θ is in degrees [33]. For a typical 2 meter satellite dish operating on C band (4 GHz), like the one shown at right, this formula gives a beam width of about 2.6^0. For the Arecibo antenna at 2.4 GHz the beam width is 0.028^0. It can be seen that parabolic antennas can produce very narrow beams, and aiming them can be a problem. Some parabolic dishes are equipped with a boresight so they can be aimed accurately at the other antenna. It can be seen there is an inverse relation between gain and beam width. By combining the beam width equation with the gain equation, the relation is[33]:

$$G = \left(\frac{\pi k}{\theta}\right) e_A \tag{2.6}$$

Chapter 3

Dielectric Materials

3.1 Introduction

A dielectric is an electrical insulator that can be polarized by an applied electric field. When a dielectric is placed in an electric field, electric charges do not flow through the material, as in a conductor, but only slightly shift from their average equilibrium positions causing dielectric polarization. Because of dielectric polarization, positive charges are displaced toward the field and negative charges shift in the opposite direction. This creates an internal electric field which reduces the overall field within the dielectric itself [34].If a dielectric is composed of weakly bonded molecules, those molecules not only become polarized, but also reorient so that their symmetry axis aligns to the field [34].

Although the term "insulator" implies low electrical conduction, "dielectric" is typically used to describe materials with a high polarizability. The latter is expressed by a number called the dielectric constant. A common, yet notable example of a dielectric is the electrically insulating material between

the metallic plates of a capacitor. The polarization of the dielectric by the applied electric field increases the capacitor's surface charge [34].

The study of dielectric properties is concerned with the storage and dissipation of electric and magnetic energy in materials [35]. It is important to explain various phenomena in electronics, optics, and solid-state physics.

3.2 Susceptibility

The electric susceptibility χ_e of a dielectric material is a measure of how easily it polarizes in response to an electric field. This, in turn, determines the electric permittivity of the material and thus influences many other phenomena in that medium, from the capacitance of capacitors to the speed of light.

It is defined as the constant of proportionality (which may be a tensor) relating an electric field E to the induced dielectric polarization density P such that

$$P = \epsilon_0 \chi_e E \tag{3.1}$$

Where ϵ_0 is the electric permittivity of free space.

The susceptibility of a medium is related to its relative permittivity by

$$\chi_e = \epsilon_r - 1 \tag{3.2}$$

So in the case of a vacuum,

$$\chi_e = 0$$

The electric displacement D is related to the polarization density P by

$$D = \epsilon_0 E + P = \epsilon_0 (1 + \chi_e) E = \epsilon_r \epsilon_0 E \tag{3.3}$$

3.3 Dispersion and Causality

In general, a material cannot polarize instantaneously in response to an applied field. The more general formulation as a function of time is

$$P(t) = \epsilon_0 \int_{-\infty}^{t} \chi_e(t - t')E(t')dt' \qquad (3.4)$$

That is, the polarization is a convolution of the electric field at previous times with time-dependent susceptibility given by $\chi_e(\Delta t)$. The upper limit of this integral can be extended to infinity as well if one defines $\chi_e(\Delta t) = 0$ for $\Delta t < 0$. An instantaneous response corresponds to Dirac delta function susceptibility $\chi_e(\Delta t) = \chi_e \delta(\Delta t)$.

It is more convenient in a linear system to take the Fourier transform and write this relationship as a function of frequency. Due to the convolution theorem, the integral becomes a simple product,

$$P(\omega) = \epsilon_0 \chi - e(\omega)E(\omega) \qquad (3.5)$$

Note the simple frequency dependence of the susceptibility, or equivalently the permittivity. The shape of the susceptibility with respect to frequency characterizes the dispersion properties of the material.

Moreover, the fact that the polarization can only depend on the electric field at previous times (i.e. $\chi_e(\Delta t) = 0$ for $\Delta t < 0$), a consequence of causality, imposes KramersKronig constraints on the susceptibility $\chi_e(0)$.

3.4 Dielectric Polarization

In the classical approach to the dielectric model, a material is made up of atoms. Each atom consists of a cloud of negative charge (Electrons) bound
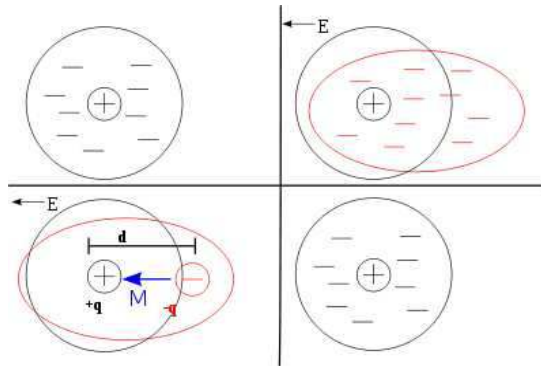
Figure 3.1: Basic atomic model of dielectric polarization.

to and surrounding a positive point charge at its center. In the presence of an electric field the charge cloud is distorted, as shown in the top right of the figure 3.1.

This can be reduced to a simple dipole using the superposition principle. A dipole is characterized by its dipole moment, a vector quantity shown in the figure as the blue arrow labelled M. It is the relationship between the electric field and the dipole moment that gives rise to the behaviour of the dielectric. (Note that the dipole moment is shown to be pointing in the same direction as the electric field. This isn't always correct, and it is a major simplification, but it is suitable for many materials.)

When the electric field is removed the atom returns to its original state. The time required to do so is the so-called relaxation time; an exponential decay.

This is the essence of the model in physics. The behaviour of the dielectric now depends on the situation. The more complicated the situation the richer the model has to be in order to accurately describe the behaviour. Important questions are:

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1. Is the electric field constant or does it vary with time?

2. If the electric field does vary, at what rate?

3. What are the characteristics of the material?

4. Is the direction of the field important (isotropy)?

5. Is the material the same all the way through (homogeneous)?

6. Are there any boundaries/interfaces that have to be taken into account?

7. Is the system linear or do nonlinearities have to be taken into account?

The relationship between the electric field E and the dipole moment M gives rise to the behaviour of the dielectric, which, for a given material, can be characterized by the function F defined by the equation:

$$M = F(E) \tag{3.6}$$

When both the type of electric field and the type of material have been defined, one then chooses the simplest function F that correctly predicts the phenomena of interest.

3.5 Dipolar Polarization

Dipolar polarization is a polarization that is either inherent to polar molecules (orientation polarization), or can be induced in any molecule in which the asymmetric distortion of the nuclei is possible (distortion polarization). Orientation polarization results from a permanent dipole, e.g. that arising from the ca. 104^0 angle between the asymmetric bonds between oxygen and hydrogen atoms in the water molecule, which retains polarization in the absence of an external electric field. The assembly of these dipoles forms a macroscopic

polarization.

When an external electric field is applied, the distance between charges, which is related to chemical bonding, remains constant in orientation polarization; however, the polarization itself rotates. This rotation occurs on a timescale which depends on the torque and the surrounding local viscosity of the molecules. Because the rotation is not instantaneous, dipolar polarizations lose the response to electric fields at the lowest frequency in polarizations. A molecule rotates about 1ps per radian in a fluid, thus this loss occurs at about 10^{11} Hz (in the microwave region). The delay of the response to the change of the electric field causes friction and heat.

When an external electric field is applied in the infrared, a molecule is bent and stretched by the field and the molecular moment changes in response. The molecular vibration frequency is approximately the inverse of the time taken for the molecule to bend, and the distortion polarization disappears above the infrared.

3.6 Ionic Polarization

Ionic polarization is polarization which is caused by relative displacements between positive and negative ions in ionic crystals (for example, NaCl).

If crystals or molecules do not consist of only atoms of the same kind, the distribution of charges around an atom in the crystals or molecules leans to positive or negative. As a result, when lattice vibrations or molecular vibrations induce relative displacements of the atoms, the centers of positive and negative charges might be in different locations. These center positions are affected by the symmetry of the displacements. When the centers don't

correspond, polarizations arise in molecules or crystals. This polarization is called ionic polarization.

Ionic polarization causes ferroelectric transition as well as dipolar polarization. The transition, which is caused by the order of the directional orientations of permanent dipoles along a particular direction, is called order-disorder phase transition. The transition which is caused by ionic polarizations in crystals is called displacive phase transition.

3.7   Dielectric Dispersion

In physics, dielectric dispersion is the dependence of the permittivity of a dielectric material on the frequency of an applied electric field. Because there is always a lag between changes in polarization and changes in an electric field, the permittivity of the dielectric is a complicated, complex-valued function of frequency of the electric field. It is very important for the application of dielectric materials and the analysis of polarization systems.

This is one instance of a general phenomenon known as material dispersion: a frequency-dependent response of a medium for wave propagation.

When the frequency becomes higher: it becomes impossible for dipolar polarization to follow the electric field in the microwave region around 10^{10} Hz; in the infrared or far-infrared region around 10^{13} Hz, ionic polarization and molecular distortion polarization lose the response to the electric field; electronic polarization loses its response in the ultraviolet region around 10^{15} Hz.

In the frequency region above ultraviolet, permittivity approaches the constant ϵ_0 in every substance, where ϵ_0 is the permittivity of the free space.

Because permittivity indicates the strength of the relation between an electric field and polarization, if a polarization process loses its response, permittivity decreases.

3.8   Dielectric relaxation

Dielectric relaxation is the momentary delay (or lag) in the dielectric constant of a material. This is usually caused by the delay in molecular polarization with respect to a changing electric field in a dielectric medium (e.g. inside capacitors or between two large conducting surfaces). Dielectric relaxation in changing electric fields could be considered analogous to hysteresis in changing magnetic fields (for inductors or transformers). Relaxation in general is a delay or lag in the response of a linear system, and therefore dielectric relaxation is measured relative to the expected linear steady state (equilibrium) dielectric values. The time lag between electrical field and polarization implies an irreversible degradation of free energy (G).

In physics, dielectric relaxation refers to the relaxation response of a dielectric medium to an external electric field of microwave frequencies. This relaxation is often described in terms of permittivity as a function of frequency, which can, for ideal systems, be described by the Debye equation. On the other hand, the distortion related to ionic and electronic polarization shows behaviour of the resonance or oscillator type. The character of the distortion process depends on the structure, composition, and surroundings of the sample.

The number of possible wavelengths of emitted radiation due to dielectric relaxation can be equated using Hemmings' first law (named after Mark

Hemmings)

$$n = \frac{l^2 - l}{2} \tag{3.7}$$

Where n is the number of different possible wavelengths of emitted radiation, l is the number of energy levels (including ground level).

3.9 Debye Relaxation

Debye relaxation is the dielectric relaxation response of an ideal, noninteracting population of dipoles to an alternating external electric field. It is usually expressed in the complex permittivity $\hat{\epsilon}$ of a medium as a function of the field's frequency ω:

$$\hat{\epsilon}(\omega) = \epsilon_\infty + \frac{\Delta \epsilon}{1 + \iota \omega \tau} \tag{3.8}$$

Where ϵ_∞ is the permittivity at the high frequency limit, $\Delta \epsilon = \epsilon_s - \epsilon_\infty$ where ϵ_s is the static, low frequency permittivity, and τ is the characteristic relaxation time of the medium[37].

Dielectric materials used for capacitors are also chosen such that they are resistant to ionization. This allows the capacitor to operate at higher voltages before the insulating dielectric ionizes and begins to allow undesirable current.

3.10 Dielectric Resonator

A dielectric resonator oscillator (DRO) is an electronic component that exhibits resonance for a narrow range of frequencies, generally in the microwave band. It consists of a "puck" of ceramic that has a large dielectric constant

and a low dissipation factor. Such resonators are often used to provide a frequency reference in an oscillator circuit. An unshielded dielectric resonator can be used as a Dielectric Resonator Antenna (DRA).

3.11 Relative Permittivity

The relative permittivity of a material under given conditions reflects the extent to which it concentrates electrostatic lines of flux. In technical terms, it is the ratio of the amount of electrical energy stored in a material by an applied voltage, relative to that stored in a vacuum. Likewise, it is also the ratio of the capacitance of a capacitor using that material as a dielectric, compared to a similar capacitor that has a vacuum as its dielectric.

The relative permittivity of a material for a frequency of zero is known as its static relative permittivity or as its dielectric constant. Other terms used for the zero frequency relative permittivity include relative dielectric constant and static dielectric constant. While they remain very common, these terms are ambiguous and have been deprecated by some standards organizations [39, 40]. The reason for the potential ambiguity is twofold. First, some older authors used "dielectric constant" or "absolute dielectric constant" for the absolute permittivity ϵ rather than the relative permittivity [41]. Second, while in most modern usage "dielectric constant" refers to a relative permittivity [40,42], it may be either the static or the frequency-dependent relative permittivity, depending on context.

Relative permittivity is typically denoted as $\epsilon_r(\omega)$ (sometimes k or K) and is defined as

$$\epsilon_r(\omega) = \frac{\epsilon(\omega)}{\epsilon_0} \tag{3.9}$$

Where $\epsilon(\omega)$ is the complex frequency-dependent absolute permittivity of the material, and ϵ_0 is the vacuum permittivity.

Relative permittivity is a dimensionless number that is in general complex. The imaginary portion of the permittivity corresponds to a phase shift of the polarization P relative to E and leads to the attenuation of electromagnetic waves passing through the medium. By definition, the linear relative permittivity of vacuum is equal to 1[42], that is $\epsilon = \epsilon_0$, although there are theoretical nonlinear quantum effects in vacuum that have been predicted at high field strengths (but not yet observed) [43].

The relative permittivity of a medium is related to its electric susceptibility, χ_e, as

$$\epsilon_r(\omega) = 1 + \chi_e. \tag{3.10}$$

3.12 Practical Relevance

The dielectric constant is an essential piece of information when designing capacitors, and in other circumstances where a material might be expected to introduce capacitance into a circuit. If a material with a high dielectric constant is placed in an electric field, the magnitude of that field will be measurably reduced within the volume of the dielectric. This fact is commonly used to increase the capacitance of a particular capacitor design. The layers beneath etched conductors in printed circuit boards (PCBs) also act as dielectrics.

Dielectrics are used in RF transmission lines. In a coaxial cable, polyethylene can be used between the center conductor and outside shield. It can also be placed inside waveguides to form filters. Optical fibers are examples of

dielectric waveguides. They consist of dielectric materials that are purposely doped with impurities so as to control the precise value of ϵ_r within the cross-section. This controls the refractive index of the material and therefore also the optical modes of transmission. However, in these cases it is technically the relative permittivity that matters, as they are not operated in the electrostatic limit.

3.13   Loss Tangent

The loss tangent is a parameter of a dielectric material that quantifies its inherent dissipation of electromagnetic energy. The term refers to the tangent of the angle in a complex plane between the resistive (lossy) component of an electromagnetic field and its reactive (lossless) component.

3.14   Electromagnetic Field Perspective

For time varying electromagnetic fields, the electromagnetic energy is typically viewed as waves propagating either through free space, in a transmission line, in a microstrip line, or through a waveguide. Dielectrics are often used in all of these environments to mechanically support electrical conductors and keep them at a fixed separation, or to provide a barrier between different gas pressures yet still transmit electromagnetic power. Maxwells equations are solved for the electric and magnetic field components of the propagating waves that satisfy the boundary conditions of the specific environment's geometry [44]. In such electromagnetic analyses, the parameters permittivity ϵ, permeability μ, and conductivity σ represent the properties of the media

through which the waves propagate. The permittivity can have real and imaginary components such that

$$\epsilon = \acute{\epsilon} - j\epsilon'' \tag{3.11}$$

If we assume that we have a wave function such that

$$E = E_0 e^{J\omega t} \tag{3.12}$$

Then Maxwell's curl equation for the magnetic field can be written as

$$d \times H = j\omega\epsilon' E + (w\epsilon'' + \sigma)E \tag{3.13}$$

Where ϵ'' is the imaginary amplitude of permittivity attributed to bound charge and dipole relaxation phenomena, which gives rise to energy loss that is indistinguishable from the loss due to the free charge conduction that is quantified by σ. The component ϵ' represents the familiar lossless permittivity given by the product of the free space permittivity and the relative permittivity, or $\epsilon' = \epsilon_0 \epsilon_r$. The loss tangent is then defined as the ratio (or angle in a complex plane) of the lossy reaction to the electric field E in the curl equation to the lossless reaction:

$$\tan\delta = \frac{\omega\epsilon'' + \sigma}{\omega\epsilon'} \tag{3.14}$$

For dielectrics with small loss, this angle is $\ll 1$ and $\tan\delta \approx \delta$. After some further maths to obtain the solution for the fields of the electromagnetic wave, it turns out that the power decays with propagation distance z as

$$P = P_0 e^{-\delta kz} \tag{3.15}$$

where P_0 is the initial power,

$$\kappa = \omega\sqrt{\mu\epsilon'} = \frac{2\pi}{\lambda} \tag{3.16}$$

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ω is the angular frequency of the wave, and λ is the wavelength in the dielectric.

There are often other contributions to power loss for electromagnetic waves that are not included in this expression, such as due to the wall currents of the conductors of a transmission line or waveguide. Also, a similar analysis could be applied to the permeability where

$$\mu = \mu' - j\mu''$$

With the subsequent definition of a magnetic loss tangent

$$\tan \delta_m = \frac{\mu''}{\mu'} \tag{3.17}$$

Chapter 4

Polymers and its types

4.1 Introduction

A polymer is a large molecule (macromolecule) composed of repeating units. These subunits are typically connected by covalent bonds. Although the term polymer is sometimes taken to refer to plastics, it actually encompasses a large class comprising both natural and synthetic materials with a wide variety of properties.

Because of the extraordinary range of properties of polymeric materials [45,46], they play an essential and ubiquitous role in everyday life [47]. This role ranges from familiar synthetic plastics and elastomers to natural biopolymers such as nucleic acids and proteins that are essential for life.

Natural polymeric materials such as shellac, amber, and natural rubber have been used for centuries. A variety of other natural polymers exist, such as cellulose, which is the main constituent of wood and paper. The list of synthetic polymers includes synthetic rubber, Bakelite, neoprene, nylon, PVC, polystyrene, polyethylene, polypropylene, polyacrylonitrile, PVB,

silicone, and many more.

Most commonly, the continuously linked backbone of a polymer used for the preparation of plastics consists mainly of carbon atoms. A simple example is polyethylene, whose repeating unit is based on ethylene monomer. However, other structures do exist; for example, elements such as silicon form familiar materials such as silicones, examples being Silly Putty and waterproof plumbing sealant. Oxygen is also commonly present in polymer backbones, such as those of polyethylene glycol, polysaccharides (in glycosidic bonds), and DNA (in phosphodiester bonds). Polymers are studied in the fields of polymer chemistry, polymer physics, and polymer science.

4.2 Polymerization

Polymerization is the process of combining many small molecules known as monomers into a covalently bonded chain. During the polymerization process, some chemical groups may be lost from each monomer. This is the case, for example, in the polymerization of PET polyester. The monomers are terephthalic acid ($HOOC-C_6H_4-COOH$) and ethylene glycol ($HO-CH_2-CH_2-OH$) but the repeating unit is $-OC-C_6H_4-COO-CH_2-CH_2-O-$, which corresponds to the combination of the two monomers with the loss of two water molecules. The distinct piece of each monomer that is incorporated into the polymer is known as a repeat unit or monomer residue.
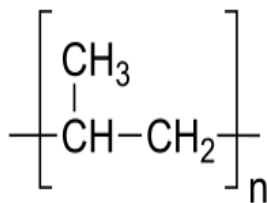
Figure 4.1: The repeating unit of the polymer polypropylene.

4.3   Polymer properties

Polymer properties are broadly divided into several classes based on the scale
at which the property is defined as well as upon its physical basis [48]. The
most basic property of a polymer is the identity of its constituent monomers.
A second set of properties, known as microstructure, essentially describe the
arrangement of these monomers within the polymer at the scale of a single
chain. These basic structural properties play a major role in determining
bulk physical properties of the polymer, which describe how the polymer
behaves as a continuous macroscopic material. Chemical properties, at the
nano-scale, describe how the chains interact through various physical forces.
At the macro-scale, they describe how the bulk polymer interacts with other
chemicals and solvents.

4.4   Chain length

The physical properties [49] of a polymer are strongly dependent on the
size or length of the polymer chain [50]. For example, as chain length is
increased, melting and boiling temperatures increase quickly [50]. Impact
resistance also tends to increase with chain length, as does the viscosity,

or resistance to flow, of the polymer in its melt state [51]. Chain length is related to melt viscosity roughly as 1:103.2, so that a tenfold increase in polymer chain length results in a viscosity increase of over 1000 times. Increasing chain length furthermore tends to decrease chain mobility, increase strength and toughness, and increase the glass transition temperature (T_g). This is a result of the increase in chain interactions such as Van der Waals attractions and entanglements that come with increased chain length. These interactions tend to fix the individual chains more strongly in position and resist deformations and matrix breakup, both at higher stresses and higher temperatures.

A common means of expressing the length of a chain is the degree of polymerization, which quantifies the number of monomers incorporated into the chain [52,53]. As with other molecules, a polymer's size may also be expressed in terms of molecular weight. Since synthetic polymerization techniques typically yield a polymer product including a range of molecular weights, the weight is often expressed statistically to describe the distribution of chain lengths present in the same. Common examples are the number average molecular weight and weight average molecular weight [54,55]. The ratio of these two values is the polydispersity index, commonly used to express the "width" of the molecular weight distribution [56]. A final measurement is contour length, which can be understood as the length of the chain backbone in its fully extended state [57]. The flexibility of an unbranched chain polymer is characterized by its persistence length.

4.5 Mechanical properties

The bulk properties of a polymer are those most often of end-use interest. These are the properties that dictate how the polymer actually behaves on a macroscopic scale.

4.5.1 Tensile strength

The tensile strength of a material quantifies how much stress the material will endure before suffering permanent deformation [58,59]. This is very important in applications that rely upon a polymer's physical strength or durability. For example, a rubber band with a higher tensile strength will hold a greater weight before snapping. In general, tensile strength increases with polymer chain length and cross linking of polymer chains.

4.5.2 Young's Modulus

Youngs modulus quantifies the elasticity of the polymer. It is defined, for small strains, as the ratio of rate of change of stress to strain. Like tensile strength, this is highly relevant in polymer applications involving the physical properties of polymers, such as rubber bands. The modulus is strongly dependent on temperature.

4.6 Applications and Processing of Polymers

Polymers play a very important role in human life. In fact, our body is made of lot of polymers, e.g. Proteins, enzymes, etc. Other naturally occurring polymers like wood, rubber, leather and silk are serving the humankind for

many centuries now. Modern scientific tools revolutionized the processing of polymers thus available synthetic polymers like useful plastics, rubbers and fiber materials. As with other engineering materials (metals and ceramics), the properties of polymers are related their constituent structural elements and their arrangement. The suffix in polymer mer is originated from Greek word meros which means part. The word polymer is thus coined to mean material consisting of many parts/mers. Most of the polymers are basically organic compounds, however they can be inorganic (e.g. silicones based on Si-O network). This chapter introduces classification of polymers, processing and synthesis of polymers, followed by mechanism of deformation and mechanical behavior of polymers.

4.7   Polymer types and Polymer synthesis & processing

Polymers are classified in several ways by how the molecules are synthesized, by their molecular structure, or by their chemical family. For example, linear polymers consist of long molecular chains, while the branched polymers consist of primary long chains and secondary chains that stem from these main chains. However, linear does not mean straight lines. The better way to classify polymers is according to their mechanical and thermal behavior. Industrially polymers are classified into two main classes plastics and elastomers.

Plastics are moldable organic resins. These are either natural or synthetic, and are processed by forming or molding into shapes. Plastics are

important engineering materials for many reasons. They have a wide range of properties, some of which are unattainable from any other materials, and in most cases they are relatively low in cost. Following is the brief list of properties of plastics: light weight, wide range of colors, low thermal and electrical conductivity, less brittle, good toughness, good resistance to acids, bases and moisture, high dielectric strength (use in electrical insulation), etc.

Plastics are again classified in two groups depending on their mechanical and thermal behavior as thermoplasts (thermoplastic polymers and thermosets (thermosetting polymers).

4.7.1 Thermoplasts

These plastics soften when heated and harden when cooled processes that are totally reversible and may be repeated. These materials are normally fabricated by the simultaneous application of heat and pressure. They are linear polymers without any cross-linking in structure where long molecular chains are bonded to each other by secondary bonds and/or inter-wined. They have the property of increasing plasticity with increasing temperature which breaks the secondary bonds between individual chains. Common thermoplasts are: acrylics, PVC, nylons, polypropylene, polystyrene, polymethyl methacrylate (plastic lenses or Perspex), etc. [60]

4.7.2 Thermosets

These plastics require heat and pressure to mold them into shape. They are formed into a permanent shape and cured or set by chemical reactions such as extensive cross-linking. They cannot be re-melted or reformed into another

shape but decompose upon being heated to too high a temperature. Thus thermosets cannot be recycled, whereas thermoplasts can be recycled. The term thermoset implies that heat is required to permanently set the plastic. Most thermosets composed of long chains that are strongly cross-linked (and/or covalently bonded) to one another to form 3-D network structures to form a rigid solid. Thermosets are generally stronger, but more brittle than thermoplasts. Advantages of thermosets for engineering design applications include one or more of the following: high thermal stability, high dimensional stability, high rigidity, light weight, high electrical and thermal insulating properties and resistance to creep and deformation under load. There are two methods whereby cross-linking reaction can be initiated cross-linking can be accomplished by heating the resin in a suitable mold (e.g. bakelite), or resins such as epoxies (araldite) are cured at low temperature by the addition of a suitable cross-linking agent, an amine. Epoxies, vulcanized rubbers, phenolics, unsaturated polyester resins, and amino resins (ureas and melamines) are examples of thermosets.

4.7.3 Elastomers

Also known as rubbers, these are polymers which can undergo large elongations under load, at room temperature, and return to their original shape when the load is released. There are number of man-made elastomers in addition to natural rubber. These consist of coil-like polymer chains those can reversibly stretch by applying a force. Processing of polymers mainly involves preparing a particular polymer by synthesis of available raw materials, followed by forming into various shapes. Raw materials for polymerization

are usually derived from coal and petroleum products. The large molecules of many commercially useful polymers must be synthesized from substances having smaller molecules. The synthesis of the large molecule polymers is known as polymerization in which monomer units are joined over and over to become a large molecule. More upon, properties of a polymer can be enhanced or modified with the addition of special materials. This is followed by forming operation. Addition polymerization and condensation polymerization are the two main ways of polymerization [60,61].

4.7.4   Addition polymerization

It is also known as chain reaction polymerization, is a process in which multifunctional monomer units are attached one at a time in chain like fashion to form linear or 3-D macro-molecule. The composition of macro-molecule is an exact multiple of that of the original reactant monomers. This kind of polymerization involves three distant stages-initiation, propagation and termination. To initiate the process, an initiator is added to the monomer. This forms free radicals with a reactive site that attracts one of the carbon atom of the monomer. When this occurs, the reactive site is transferred to other carbon atom in the monomer and a chain begins to form in propagation stage. A common initiator is benzoyl peroxide. When polymerization is nearly complete, remaining monomers must diffuse a long distance to reach reactive site, thus growth rate decreases.

The process for polyethylene is as shown in figure 4.2. Where R represents the active initiator. Propagation involves the linear growth of the molecule as monomer units become attached to one another in succession to produce the
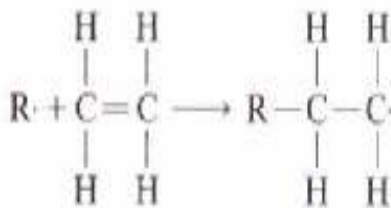
Figure 4.2: Process for polyethylene.

chain molecule, which is represented, again for polyethylene, as is represented in figure 4.3.
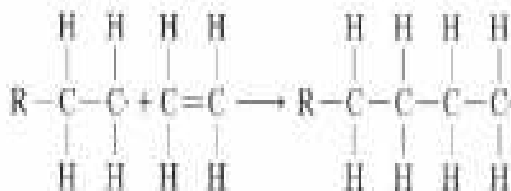
Figure 4.3: Process for polyethylene.

As we need polymers with controlled molecular weight, polymerization needs to be terminated at some stage. Propagation may end or terminate in different ways. First, the active ends of two propagating chains may react or link together to form a non-reactive molecule, figure 4.4.
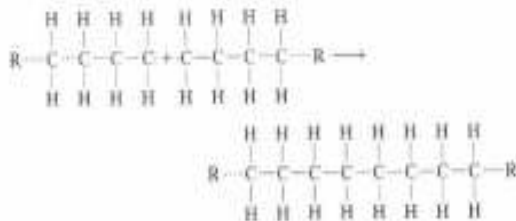
Figure 4.4: Process for polyethylene.

Thus terminating the growth of each chain or an active chain end may react with an initiator or other chemical species having a single active bond as shown in figure 4.5.
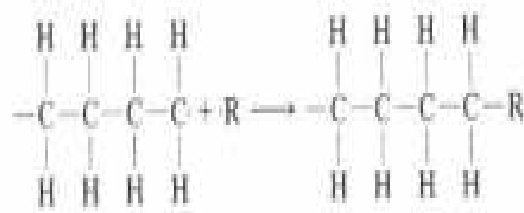
Figure 4.5: Process for polyethylene.

With the resultant cessation of chain growth. Polyethylene, polypropylene, PVC, and polystyrene are synthesized using addition polymerization.

4.7.5 Condensation polymerization

Also known as step growth polymerization, involves more than one monomer species; and there is usually a small molecular weight by-product such as water, which is eliminated. The repeat unit here forms from original monomers, and no product has the chemical formula of mere one mer repeat unit. The polymerization of dimethyl terephthalate and ethylene glycol to produce polyester is an important example. The by-product, methyl alcohol, is condensed off and the two monomers combine to produce a larger molecule (mer repeat unit). Another example, consider the formation of polyester from the reaction between ethylene glycol and adipic acid; the intermolecular reaction is as follows:

This stepwise process is successively repeated, producing, in this case, a linear molecule. The intermolecular reaction occurs every time a mer repeat
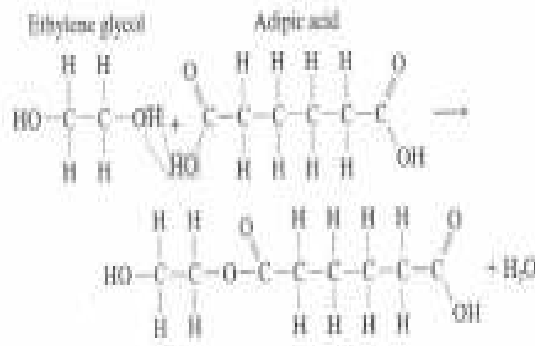
Figure 4.6: Process for polyethylene.

unit is formed. Reaction times for condensation are generally longer than for addition polymerization. Polyesters, phenol-formaldehyde, nylons, polycarbonates etc are produced by condensation polymerization. Condensation polymerization reactions also occur in sol-gel processing of ceramic materials. Some polymers such as nylon may be polymerized by either technique.

' Polymers, unlike organic/inorganic compounds, do not have a fixed molecular weight. It is specified in terms of degree of polymerization number of repeat units in the chain or ration of average molecular weight of polymer to molecular weight of repeat unit. Average molecular weight is however defined in two ways. Weight average molecular weight is obtained by dividing the chain into sizes ranges and determining the fraction of chains having molecular weights within that range. Number average molecular weight is based on the number fraction, rather than the weight fraction, of the chains within each size range. It is always smaller than the weight average molecular weight . Most of polymer properties are intrinsic i.e. characteristic of a specific polymer. Foreign substances called additives are intentionally introduced to enhance or modify these properties. These include fillers,

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plasticizers, stabilizers, colorants, and flame retardants. Fillers are used to improve tensile and compressive strength, abrasion resistance, dimensional stability etc. wood flour, sand; clay, talc etc are example for fillers. Plasticizers aid in improving flexibility, ductility and toughness of polymers by lowering glass transition temperature of a polymer. These are generally liquids of low molecular weight. Stabilizers are additives which counteract deteriorative processes such as oxidation, radiation, and environmental deterioration. Colorants impart a specific color to a polymer, added in form of either dyes (dissolves) or pigments (remains as a separate phase). Flame retardants are used to enhance flammability resistance of combustible polymers. They serve the purpose by interfering with the combustion through the gas phase or chemical reaction. Polymeric materials are formed by quite many different techniques depending on (a) whether the material is thermoplast or thermoset, (b) melting/degradation temperature, (c) atmospheric stability, and (d) shape and intricacy of the product. Polymers are often formed at elevated temperatures under pressure. Thermoplasts are formed above their glass transition temperatures while applied pressure ensures that the product retain its shape. Thermosets are formed in two stages making liquid polymer, then molding it [61,62]. Different molding techniques are employed in fabrication of polymers. Compression molding involves placing appropriate amount of polymer with additives between heated male and female mold parts. After pouring polymer, mold is closed, and heat and pressure are applied, causing viscous plastic to attain the mold shape. Figure-4.7 shows a typical mould employed for compression molding.

Figure 4.7: Schematic diagram of a mould employed for compression
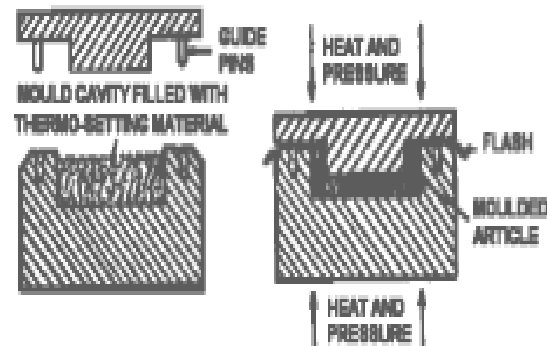
Figure 4.7: Process for polyethylene.

molding

Transfer molding differs from compression molding in how the materials is introduced into the mold cavities. In transfer molding the plastic resin is not fed directly into the mold cavity but into a chamber outside the mold cavities. When the mold is closed, a plunger forces the plastic resin into the mold cavities, where and molded material cures. In injection molding, palletized materials is fed with use of hopper into a cylinder where charge is pushed towards heating chamber where plastic material melts, and then molten plastic is impelled through nozzle into the enclosed mold cavity where product attains its shape. Most outstanding characteristic of this process is the cycle time which is very short. The schematic diagram of injection-molding machine is shown figure 4.8.

Extrusion is another kind of injection molding, in which a thermoplastic material is forced through a die orifice, similar to the extrusion of metals. This technique is especially adapted to produce continuous lengths with constant cross-section. The schematic diagram of a simple extrusion machine is shown in fig 4.9,
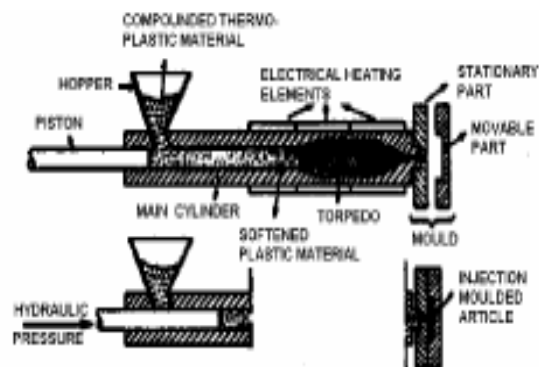
Figure 4.8: Process for polyethylene.
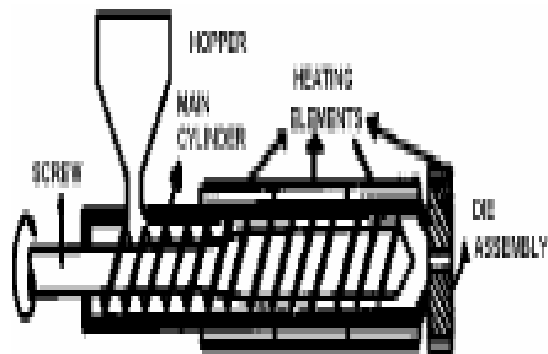
Figure 4.9: Process for polyethylene.

Figure 4.9: Schematic diagram of a simple extrusion machine

Blow molding of plastics is similar to blowing of glass bottles. Polymeric materials may be cast similar to metals and ceramics

4.8 Crystallization, melting and glass transition

Polymers are known by their high sensitivity of mechanical and/or thermal properties. This section explains their thermal behavior. During processing of polymers, they are cooled with/without presence of presence from liquid state to form final product. During cooling, an ordered solid phase may be formed having a highly random molecular structure. This process is called crystallization. The melting occurs when a polymer is heated. If the polymer during cooling retains amorphous or non-crystalline state i.e. disordered molecular structure, rigid solid may be considered as frozen liquid resulting from glass transition. Thus, enhancement of either mechanical and/or thermal properties needs to consider crystallization, melting, and the glass transition.

Crystallization and the mechanism involved play an important role as it influences the properties of plastics. As in solidification of metals, polymer crystallization involves nucleation and growth. Near to solidification temperature at favorable places, nuclei forms, and then nuclei grow by the continued ordering and alignment of additional molecular segments. Extent of crystallization is measured by volume change as there will be a considerable change in volume during solidification of a polymer. Crystallization rate is dependent on crystallization temperature and also on the molecular weight of the polymer. Crystallization rate decreases with increasing molecular weight.

Melting of polymer involves transformation of solid polymer to viscous liquid upon heating at melting temperature, T_m. Polymer melting is dis-

tinctive from that of metals in many respects - melting takes place over a temperature range; melting behavior depends on history of the polymer; melting behavior is a function of rate of heating, where increasing rate results in an elevation of melting temperature. During melting there occurs rearrangement of the molecules from ordered state to disordered state. This is influenced by molecular chemistry and structure (degree of branching) along with chain stiffness and molecular weight.

Glass transition occurs in amorphous and semi-crystalline polymers. Upon cooling, this transformation corresponds to gradual change of liquid to rubbery material, and then rigid solid. The temperature range at which the transition from rubbery to rigid state occurs is termed as glass transition temperature, Tg. This temperature has its significance as abrupt changes in other physical properties occur at this temperature. Glass transition temperature is also influenced by molecular weight, with increase of which glass transition temperature increases. Degree of cross-linking also influences the glass transition such that polymers with very high degree of cross-linking do not experience a glass transition. The glass transition temperature is typically 0.5 to 0.75 times the absolute melting temperature. Above the glass transition, non-crystalline polymers show viscous behavior, and below the glass transition they show glass-brittle behavior (as chain motion is very restricted), hence the name glass transition [62].

Melting involves breaking of the inter-chain bonds, so the glass and melting temperatures depend on: Chain stiffness (e.g., single vs. double bonds) Size, shape of side groups Size of molecule Side branches, defects cross-linking

4.9　Mechanical behavior of polymers

Polymer mechanical properties can be specified with many of the same parameters that are used for metals such as modulus of elasticity, tensile/impact/fatigue strengths, etc. However, polymers are, in many respects, mechanically dissimilar to metals. To a much greater extent than either metals or ceramics, both thermal and mechanical properties of polymers show a marked dependence on parameters namely temperature, strain rate, and morphology. In addition, molecular weight and temperature relative to the glass transition play an important role that are absent for other type of materials.

A simple stress- strain curve can describe different mechanical behavior of various polymers. As shown in figure 4.10, the stress-strain behavior can be brittle, plastic and highly elastic (elastomeric or rubber-like). Mechanical properties of polymers change dramatically with temperature, going from glass-like brittle behavior at low temperatures to a rubber-like behavior at high temperatures. Highly crystalline polymers behave in a brittle manner, whereas amorphous polymers can exhibit plastic deformation. These phenomena are highly temperature dependent, even more so with polymers than they are with metals and ceramics. Due to unique structures of cross-linked polymers, recoverable deformations up to very high strains / point of rupture are also observed with polymers (elastomers). Tensile modulus (modulus) and tensile strengths are orders of magnitude smaller than those of metals, but elongation can be up to 1000% in some cases. The tensile strength is defined at the fracture point and can be lower than the yield strength.

Figure-4.10: Typical stress-strain curves for polymers. As the tempera-
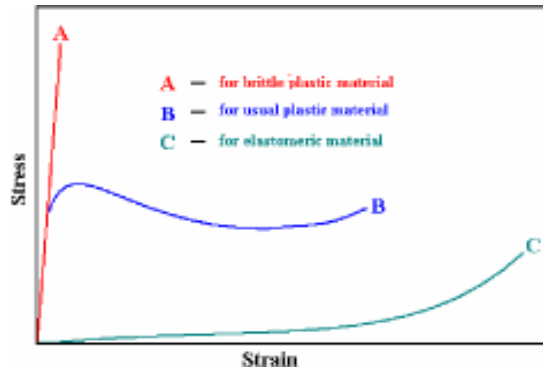
Figure 4.10: Process for polyethylene.

ture increases, both the rigidity and the yield strength decrease, while the elongation increases. Thus, if high rigidity and toughness are the requirements, the temperature consideration is important. In general, decreasing the strain rate has the same influence on the strain-strength characteristics as increasing the temperature: the material becomes softer and more ductile. Despite the similarities in yield behavior with temperature and strain rate between polymers, metals, and ceramics, the mechanisms are quite different. Specifically, the necking of polymers is affected by two physical factors that are not significant in metals: dissipation of mechanical energy as heat, causing softening magnitude of which increases with strain rate; deformation resistance of the neck, resulting in strain-rate dependence of yield strength. The relative importance of these two factors depends on materials, specimen dimensions and strain rate. The effect of temperature relative to the glass transition is depicted in terms of decline in modulus values. Shallow decline of modulus is attributed to thermal expansion, whereas abrupt changes are attributable to viscoelastic relaxation processes. Together molecular weight and crystallinity influence a great number of mechanical properties of poly-

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mers including hardness, fatigue resistance, elongation at neck, and even impact strength. The chance of brittle failure is reduced by raising molecular weight, which increases brittle strength, and by reducing crystallinity. As the degree of crystallinity decreases with temperature close to melting point, stiffness, hardness and yield strength decrease. These factors often set limits on the temperature at which a polymer is useful for mechanical purposes.

Elastomers, however, exhibit some unique mechanical behavior when compared to conventional plastics. The most notable characteristics are the low modulus and high deformations as Elastomers exhibit large, reversible elongations under small applied stresses. Elastomers exhibit this behavior due to their unique, cross-linked structure [61,62].

Elastic modulus of elastomers (resistances to the uncoiling of randomly orientated chains) increases as with increase in temperature. Unlike non-cross-linked polymers, elastomers exhibit an increase inelastic modulus with cross-link density.

4.10   Mechanisms of deformation and strengthening of polymers

An understanding of deformation mechanisms of polymers is important in order to be able to manage the optimal use of these materials, a class of materials that continues to grow in terms of use in structural applications. Despite the similarities in ductile and brittle behavior with to metals and ceramics respectively, elastic and plastic deformation mechanisms in polymers are quite different. This is mainly due to (a) difference in structure

they made of and (b) size of the entities responsible for deformation. Plastic deformation in metals and ceramics can be described in terms of dislocations and slip planes, whereas polymer chains must undergo deformation in polymers leading to different mechanism of permanent deformation. Unique to most of the polymers is the viscoelasticity means when an external force is applied, both elastic and plastic (viscous) deformation occur. For viscoelastic materials, the rate of strain determines whether the deformation in elastic or viscous. The viscoelastic behavior of polymeric materials is dependent on both time and temperature. Plastic polymers deform elastically by elongation of the chain molecules from their stable conformations in the direction of the applied stress by the bending and stretching of the strong covalent bonds. In addition, there is a possibility for slight displacement of adjacent molecules, which is resisted by weak secondary / van-der Waals bonds. Plastic deformation in polymers is not a consequence of dislocation movement as in metals. Instead, chains rotate, stretch, slide and disentangle under load to cause permanent deformation. This permanent deformation in polymers might occur in several stages of interaction between lamellar and intervening amorphous regions. Initial stages involve elongation of amorphous tie chains, and eventual alignment in the loading direction. Continues deformation in second stage occurs by the tilting of the lamellar blocks. Next, crystalline block segments separate before blocks and tie chains become orientated in the direction of tensile axis in final stage. This leads to highly orientated structure in deformed polymers. Elastomers, on the other hand, deform elastically by simple uncoiling, and straightening of molecular chains that are highly twisted, kinked, and coiled in unstressed state. The driving

force for elastic deformation is change in entropy, which is a measure of degree of disorder in a system. When an elastomer is stretched, the systems order increases. If elastomer is released from the applied load, its entropy increases. This entropy effect results in a rise in temperature of an elastomer when stretched. It also causes the modulus of elasticity to increase with increasing temperature, which is opposite to the behavior of other materials. Fracture of polymers is again dependent on morphology of a polymer. As a thumb rule, thermosets fracture in brittle mode. It involves formation of cracks at regions where there is a localized stress concentration. Covalent bonds are severed during the fracture [62]. However, both ductile and brittle modes are possible mode of fracture for thermoplasts. Many of thermoplasts can exhibit ductile-to-brittle transition assisted by reduction in temperature, increase in strain rate, presence of notch, increased specimen thickness and a modification of the polymer structure. Unique to polymer fracture is crazing present of regions of very localized yielding, which lead to formation of small and interconnected micro voids. Crazes form at highly stressed regions associated with scratches, flaws and molecular inhomogeneties; and they propagate perpendicular to the applied tensile stress and typically are $5\mu m$ or less thick. A craze is different from a crack as it can support a load across its face.

The deformation of plastic materials can be primarily elastic, plastic, or a combination of both types. The deformation mode and resistance of deformation depends on many parameters for different plastics. The following factors influence the strength of a thermoplast: average molecular mass, degree of crystallization, presence of side groups, presence of polar and other

specific atoms, presence of phenyl rings in main chains and addition of reinforcements. Effect of every one of these factor can be used to strengthen a thermoplast. Thermosets are, however, strengthened by reinforcement methods.

Strength of a thermoplast is directly dependent on its average molecular mass since polymerization up to a certain molecular-mass range is necessary to produce a stable solid. This method is not used so often as after a critical mass range, increasing the average molecular mass does not greatly increase its strength. In general, as the degree of crystallinity increases, the strength, modulus and density all increase for a thermoplast. Another method to increase the strength is to create more resistance to chain slippage. This can be achieved by addition of bulky side groups on main chains, which results in increase of strength but reduces the ductility. Increased resistance to chain slippage can be achieved by increasing the molecular bonding forces between the polymer chains. E.g.: introducing a chlorine atom on every other carbon atom of main chain to make polyvinylchloride (PVC). Introducing an ether linkage (i.e. introduction of oxygen atom) or amide linkage (i.e. introduction of oxygen and nitrogen atoms) into the main chain can increase the rigidity of thermoplasts. One of the most important strengthening methods for thermoplasts is the introduction of phenylene rings in the main chain. It is commonly used for high-strength engineering plastics. The phenylene rings cause steric hindrance to rotation within the polymer chain and electronic attraction of resonating electrons between adjacent molecules. Another method of strengthening is introduction of reinforcements like glass fibers. Glass content ranges from 20 to 40%, depending on trade-off between

desired strength, ease of processing and economics. Thermosets are strengthened by reinforcements again. Different reinforcements are in use according to the necessity. Glass fibers are most commonly used to form structural and molding plastic compounds. Two most important types of glass fibers are E (electrical) - and S (high strength)- glasses. E-glass (lime-aluminum-borosilicate glass with zero or low sodium and potassium levels) is often used for continuous fibers. S-glass (65% SiO_2, 25% $Al2O_3$ and 10% MgO) has higher strength-to-weight ratio and is more expansive thus primary applications include military and aerospace applications. Carbon fiber reinforced plastics are also often used in aerospace applications. However they are very expansive. The other classes of reinforcements include aramid (aromatic polyamide) fibers. They are popularly known as Kevlar. Presently two commercial variants of Kevlar are available Kevlar29 and Kevlar49. Kevlar29 is a low-density, high strength aramid fiber designed for applications such as ballistic protection, ropes and cables. Kevlar49 is characterized by a low density and high strength/modulus; is used in aerospace, marine, automotive and other industrial applications. Thermosets without reinforcements are strengthened by creation of network of covalent bonds throughout the structure of the material. Covalent bonds can be developed during casting or pressing under heat and pressure [61,62].

4.11 Characteristics and typical applications of few plastic materials

a) Thermo plastics

1. Acrylonitrile-butadiene-styrene (ABS):

Characteristics: Outstanding strength and toughness, resistance to heat distortion; good electrical properties; flammable and soluble in some organic solvents.

Application: Refrigerator lining, lawn and garden equipment, toys, highway safety devices.

2. Acrylics (poly-methyl-methacrylate)

Characteristics: Outstanding light transmission and resistance to weathering; only fair mechanical properties.

Application: Lenses, transparent aircraft enclosures, drafting equipment, outdoor signs

3. Fluorocarbons (PTFE or TFE)

Characteristics: Chemically inert in almost all environments, excellent electrical properties; low coefficient of friction; may be used to $260\,^\circ C$; relatively weak and poor cold-flow properties.

Application: Anticorrosive seals, chemical pipes and valves, bearings, anti adhesive coatings, high temperature electronic parts.

4. Polyamides (nylons)

Characteristics: Good mechanical strength, abrasion resistance, and toughness; low coefficient of friction; absorbs water and some other liquids.

Application: Bearings, gears, cams, bushings, handles, and jacketing for wires and cables

5. Polycarbonates

Characteristics: Dimensionally stable: low water absorption; transparent; very good impact resistance and ductility.

Application: Safety helmets, lenses light globes, base for photographic film

6. Polyethylene

Characteristics: Chemically resistant and electrically insulating; tough and relatively low coefficient of friction; low strength and poor resistance to weathering.

Application: Flexible bottles, toys, tumblers, battery parts, ice trays, film wrapping materials.

7. Polypropylene

Characteristics: Resistant to heat distortion; excellent electrical properties and fatigue strength; chemically inert; relatively inexpensive; poor resistance to UV light.

Application: Sterilizable bottles, packaging film, TV cabinets, luggage

8. Polystyrene

Characteristics: Excellent electrical properties and optical clarity; good thermal and dimensional stability; relatively inexpensive

Application: Wall tile, battery cases, toys, indoor lighting panels, appliance housings.

9. Polyester (PET or PETE)

Characteristics: One of the toughest of plastic films; excellent fatigue and tear strength, and resistance to humidity acids, greases, oils and solvents

Application: Magnetic recording tapes, clothing, automotive tire cords, beverage containers.

b) Thermo setting polymers

1. Epoxies Characteristics: Excellent combination of mechanical proper-

ties and corrosion resistance; dimensionally stable; good adhesion; relatively inexpensive; good electrical properties.

Application: Electrical moldings, sinks, adhesives, protective coatings, used with fiberglass laminates.

2. Phenolics

Characteristics: Excellent thermal stability to over $150\,^\circ C$; may be compounded with a large number of resins, fillers, etc.; inexpensive.

Application: Motor housing, telephones, auto distributors, electrical fixtures.

Chapter 5

Effect of Dielectric and Polymer Material on Various Antennas

Polymers intended for microwave antennas should have a dielectric constant between 1.5 to 3.0 and tan loss factor less than 0.001 for high gain, small beam-width operation. Desirable antenna properties are obtained by polymerizing the monomers using UV & gamma-radiations compared to polymerization with the use of initiators. The polymer should be able to withstand shock, vibration and high ambient temperature. Teflon has proved to be the polymer of choice followed by polystyrene, Perspex, nylon, polypropylene and polyacetal.

A dielectric polymer rod can act as a guide of electromagnetic waves especially in the microwave frequency region. Properly designed end fire antennas can realize gains in excess of 18db in the 8.5 - 12.8 GHz frequency range [63-

66]. The gain-frequency characteristics are directly dependent on the dielectric constant ϵ_r and tan loss factor of the polymer. The polymer studied for antenna applications are Teflon, polystyrene, Perspex, nylon, polypropylene and polyacetal.

5.1 Effect of Dielectric constant ϵ_r on Gain:

The polyrod antenna gain and radiation characteristics are dependent on the diameter d, and are a function of dielectric constant ϵ_r . For a given polymer the rod diameter determines the wave velocity v, and the gain is optimized when v, and the antenna length l satisfies the Hansen-Woodyard condition [67]. It has been established that polyrod realizes maximum directive gain when

$$d = \lambda_0/\sqrt{A\pi(\epsilon_r - 1)} \tag{5.1}$$

Where A is the constant to be determined for a polymer at the free-space wave length. Typical values of A for Perspex (ϵ_r=2.56) and Teflon (ϵ_r =2.1) at 10.0 GHZ are 1.51 and 1.15 respectively. Since $d \propto 1/\sqrt{\epsilon_r}$, it follows that a large dielectric constant ϵ_r results in the small diameter of the antenna. This is not desirable particularly in operating conditions subjected to shock, vibration and high ambient temperature. Studies show that dielectric constant ϵ_r values in the range 1.5-3.0 are suitable for microwave antenna. Polymers with these ϵ_r values are Teflon, polystyrene, Perspex, nylon, polypropylene and polyacetal. For wide frequency operation the dielectric constant should not vary by in the frequency spectrum at which the application is desired.

5.2 Effect of tanδ loss factor on gain

The gain of the antenna is also affected by the length and the tanloss of the polyrod. It has been observed that antenna length between 6-8 wavelengths realizes optimum gain and small beam-width. The antenna attenuation of microwave power inside the polymer is related to l, dielectric constant ϵ_r and tanδloss factor by the expression,

$$\alpha = \frac{27.3}{\lambda_0}.\sqrt{\epsilon_r}.tan\delta \quad dB/cm \qquad (5.2)$$

To minimize attenuation it thus becomes necessary to select a polymer with small dielectric constant ϵ_r and tanloss, and also the antenna length. A 6.5 wavelength long antenna using a polymer with dielectric constant ϵ_r = 2.0 and $tan\delta$ loss = 0.001 attenuates the signal 0.014 dB/cm at 10.0GHZ. Clearly, antennas with l = 6 8 wavelengths utilizing polymers with dielectric constant $\epsilon_r \leq$ 3.0 and tanless than 0.001 should be used to minimize the attenuation losses and thereby increase the directive gain of the antenna.

It is also desirable that the polymer with suitable dielectric constant ϵ_r and tan values be adaptable for fabrication into antennas of various profiles. The polymer should be able to stand ambient temperature up to 1000 c without changing form and electrical parameters. For moulded antennas it is preferable that the monomers be polymerized with the addition of initiators as this has the adverse effect on the dielectric properties. UV and Co^{60} gamma radiated monomers have resulted in stable polymers [63].

Circular and rectangular polymer antennas were designed for X-band frequencies using various polymers. Maximum directive gain of 18.5 dB was obtained for Teflon rectangular antennas in the 9.5-10.5GHZ frequency range. The gain obtained for circular antenna in the same frequency range was 16.5

dB. Table below gives the gain obtained for circular antennas using various polymers. The input impedance of the Teflon antenna does not vary appre-

Table 5.1: Gain obtained for circular antenna using various polymers.

Polymer	Polystyrene	Nylon	Perspex	Polypropleyne	Polyacetal
Gain,dB	16.65	16.2	15.0	14.4	14.3
-3dB beam-width	20^0	16^0	19.6^0	21.2^0	18^0

ciably with frequency and this is reflected in the wide-band operation with fairly stabilized gain.

A dielectric rod can act as a guide for electromagnetic waves, and this property has been utilized in the design of various types of antennas since 1950 [68-72]. The guiding action is usually imperfect since considerable electromagnetic power escapes through the walls of di-electric rod and is radiated from its surface. This tendency of dielectric to radiate micro-wave frequencies is turned to advantage in the design of dielectric rod antennas of various profiles namely circular [66,77], rectangular[70,71] and tapered version of the same so as to collimate the electromagnetic radiation in a particular direction. Almost all of these antennas act as end-fire antennas. Design theories have been developed in order to optimize the gain and radiation characteristic of these antennas by various authors [75,76,81]. It has been reported in the literature that microwave circular and rectangular polymer dielectric endfire antennas realize gains in excess of 17dB with the half power beam width of 18 degrees or below in the X-band frequencies 8.5-12.8GHZ [71,75]. The

polymer materials found suitable at these frequencies are Teflon, polystyrene, Perspex, nylon, polypropylene and polyacetal.

The use of horn antennas for high gain and well defined radiation characteristic for transmission and reception of microwave frequencies is well recognized for last 50 years. A horn antenna is primarily characterized by a wave guide that is flared so that the wave inside the guide expands in an orderly manner. The field distribution across the mouth of the horn antenna serves as a source of radiation and thus acts as an alternative means of producing field distribution as compared to that of the parabolic reflector. It is observed that for horn antennas, very small flare angles give the sharpest beam (low-3dB beam width) and highest power gains for a given mouth size. However, horn antennas find extensive use at microwave frequencies where power gain requirement are moderated. High gains can only be achieved for much larger dimensions of the mouth, thereby putting it in an disadvantage [76,79]. The characteristics of horn antennas can be improved to suit particular applications by loading its aperture with dielectric slab or by simply coating the walls of horn antennas and wave guide with dielectric polymer materials described earlier. This technique when optimized can result in desirable gain-radiation characteristic, namely high directivity, small beam-width and considerably more gain than of the horn antenna by itself.

Antennas with high gain performance are the required for some of the applications in communication systems. The conventional high-gain antennas most often used are parabolic reflectors. Although they are efficient radiators, parabolic reflectors are too large and heavy, due to their curved reflecting surfaces. As a result, a planar reflector called a microstrip reflec-

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tarray was being proposed as a future candidate high-gain antenna [84]. It consists of an array of microstrip patches on the grounded dielectric substrate and is illuminated by a primary feed horn which is placed at a particular distance from the array whose individual elements are designed to scatter the incident field with proper phase distribution required to form a planar phase surface in front of the aperture [85]. The reflectarray antenna can achieve a very high efficiency for a very large aperture and it can also be designed to tilt a large angle [86]. Despite of the advantage of the size, cost and easy deployability, the major deficiency of the reflectarray that limits its usage is the low bandwidth performance [87]. The main factors that limit the bandwidth of reflectarray antenna are the narrow bandwidth of patch elements which is caused by the extended path length between the feed horn and the reflectarray, and the phase errors related to the change in patch size [88]. The feed antenna bandwidth and array element spacing also limits the bandwidth of reflectarrays but these two are not serious concerns if the bandwidth requirement is less than 15% [84]. Another important factor, that affects the bandwidth of the reflectarray antenna and has not been discussed in the past thoroughly, is the selection of suitable dielectric material.

5.3 Distinction of Different Types of Losses in Reflectarray Antennas

Generally the reflection loss of the reflectarray antennas is primarily limited to dielectric absorption in the dielectric layer and conductor loss [89]. The reflection loss of reflectarray antenna depends on the material properties

of the dielectric material which includes the substrate thickness, and the conducting material used for the patch element and the ground plane as given in equation below:

$$R_l = \alpha_d + \alpha_c \qquad (5.3)$$

Where, R_l is the reflection loss and α_d and α_c represent the attenuation factor due to dielectric and conductor loss. The dielectric loss occurs due to the strong electric fields in the substrate region and copper loss occurs due to high current generated on the top surface of the patch element [90].

The electric field distribution and the surface currents are highest at resonance which is the reason of the highest loss at the resonant frequency. For further investigation of the loss mechanism in a reflectarray antenna, an infinite reflectarray with 0.035mm patch element thickness and 1mm substrate thickness using commercially available CST computer model is designed. Different dielectric materials are used and the dielectric loss is observed by reducing the conductor loss to minimum (or ideally zero by using PEC for patch element and ground plane). Copper with a conductivity of 59.6Ms/m is used for the design of patch element and the ground plane in order to introduce the conductor loss in the reflectarray antenna design. Copper loss or the conductor loss is observed separately by defining the loss tangent value of the dielectric substrate to be zero and hence making the factor due to dielectric loss to be zero. It has been observed that the materials with high loss tangent values, such as CEM and Gallium Arsenide have very high reflection loss and the main contributor for this high reflection loss is dielectric loss. This is because these materials exhibit high dielectric absorption in the dielectric layer of the reflectarray antennas. On the other hand materials with low loss

tangent values such as Teflon and Alumina have relatively very low reflection loss. This is due to low dielectric loss properties and the dominant loss for this type of reflectarray antenna design is caused by conductor/copper loss. It has been observed that Teflon which has a low loss tangent value ($tan\delta = 0.0004$) has very low dielectric loss and Gallium Arsenide which has a high loss tangent value ($tan\delta = 0.006$) offers a very high dielectric loss as compared to the copper loss.

5.4 Bandwidth Performance of Reflectarrays Using Different Materials

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It has been seen that as the dielectric permittivity of the material used for the reflectarray design is increased, the bandwidth decreases. Gallium Arsenide, which has the highest dielectric permittivity (ϵ_r=13) has the minimum 10% and 20% bandwidths of 84 MHz and 126MHz respectively while Teflon which has the lowest dielectric permittivity(ϵ_r =2.08) has the highest 10% and 20% bandwidths of 360 MHz and 540 MHz respectively.

Infinite rectangular microstrip reflectarray antennas with different dielectric materials are analyzed in terms of bandwidth and reflection loss performance and it has been shown that the bandwidth of the reflectarray antenna can be increased by using a suitable dielectric material. It has been shown that Teflon (ϵ_r =2.08 and $tan\delta = 0.0004$) has maximum bandwidth performance compared to Gallium Arsenide (ϵ_r =2.08 and $tan\delta = 0.0004$) which has minimum value of the bandwidth measured at different levels of the

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reflection loss curve.

The developments of microwave dielectric materials for applicationsin communication systems, such as cellular phones, wireless local area networks, direct broadcasting satellite (DBS), and global positioning systems, have evolved in an unprecedented path for the last decade [91,92]. Moreover, extension of the carrier frequency from industrial, scientific, and medical(ISM) bands to the millimeter wave range is expected in the near future as the research on ultrahigh-speed communication systems is currently underway. The unique electrical properties of ceramic dielectric materials have revolutionized the microwave based wireless communications industry by reducing the size and the cost of components in circuit systems. In order to properly select materials for microwave application, three dielectric properties need to be considered: the dielectric constant (ϵ_r), the quality factor (Qf), and the stability of the temperature coefficient of the resonant frequency (τ_f). A high dielectric constant material can effectively reduce the size of resonators as the wavelength (λ) in dielectrics is inversely proportional to $\sqrt{\epsilon_r}$ according to the relation $\lambda = \lambda_0/\sqrt{\epsilon_r}$ where λ is the wavelength in vacuum . The inverse of the dielectric loss ($Q = 1/tan\delta$) is required to be high in order to achieve prominent frequency selectivity and stability for microwave transmitter components, of which a small temperature coefficient of the resonant frequency [93] ensures the stability of the microwave components at different working temperatures. However, as the frequency of interest is shifted from 900 MHz to 2.4, 5.2, 5.8 GHz, or even to the millimeter wave range, materials with a high dielectric constant tend to be of less interest. On the other hand, high quality factor would play a more prominent role instead, as $Q \times f$

is almost constant in the microwave and millimeter wave regions. In general, high dielectric constant materials exhibit high dielectric loss (low $Q \times f$ value), while low-loss ceramics are usually accompanied by a low ϵ_r value. Low-loss dielectrics, however, would normally require high sintering temperatures. In fact, using the low-melting glass additive, chemical processing, and small-sized particle as starting materials can effectively reduce the sintering temperature of the dielectric materials [94-96].Alumina is a well-known material for substrates, dielectric resonators, and patch antennas. Commercially available alumina normally has a $Q \times f$ value around 100 000-200 000 GHz. When 0.5 wt% TiO2 is added, alumina ceramics prepared at 1500 °C for 5 h possesses a quality factor ($Q \times f$) of 450 000 GHz. Using nano-sized powder as the starting material, $\alpha - Al_2O_3$ ceramics can be sintered at C1500 °C, with its $Q \times f$ value subsequently elevated to 515 000 GHz without a further addition [98]. For practical applications, it is required to have a τ_f value as close to zero as possible. Shifting of the f value can be achieved by post-annealing treatment due to the decomposition of the Al_2TiO_5 phase [99,100]. It also possesses a $Q \times f$ value of 148 000GHz at 1350 °C. Using two or more compounds with negative and positive temperature coefficient values to form a solid solution or mixed phases, however, is the most promising method to obtain a zero temperature coefficient of resonant frequency. As most of the dielectric ceramics with high dielectric constant shave positive f values, it is thereby desirable to search for material shaving a high dielectric constant, high Q, and negative τ_f in order to achieve this goal. Therefore, TiO2 (ϵ_r =100, $Q \times f = 50\ 000$ GHz, $\tau_f = 5450ppm/\,°C$)[101] has often been utilized in controlling microwave dielectric properties and the sintering

behavior[102,103].

The selection of the dielectric material is of key importance in the design of microstrip antennas, affecting mechanical, thermal and electrical performance. The dielectric substrate in a microstrip antenna mainly serves as mechanical support for the patch providing uniform spacing and mechanical stability. Lower values of relative dielectric constant (normally between 1 and 2) can be obtained by using polystyrene foam or honeycomb structures. Dielectrics based on fiberglass reinforced Teflon, also known as PTFE (polytetra-fluoroethylene), typically provide a relative dielectric constant between 2 and 4. Higher values can be obtained through materials based on ceramic, quartz or alumina. However, these materials should be carefully employed as they provide a reduction in the patch size at the expense of radiation efficiency and mechanical stability. Another important selection driver for microstrip antenna substrates are dielectric losses. Acceptable dielectric losses are usually related to the application requirements and to the antenna architecture. In general, low tangent loss results in higher dielectric cost.

In the last few years, the complexity of microstrip antennas has constantly increased. In particular, multilayer configurations with a high integration level and many vertical transitions are becoming ever-more popular. In general, the development of multilayer assemblies can be particularly difficult as layers with different materials are usually employed for the circuit elements and for the antennas. Indeed, dielectrics of low dielectric constant are preferred for radiating structures whereas materials with high permittivity are usually employed for microwave circuits. This difference usually

results in different coefficients of thermal expansion which can generate mechanical deformations of the multilayer structure. For this reason, new types of materials and fabrication processes are attracting the attention of many researchers. In particular, interesting results [104] have been obtained with liquid crystal polymers (LCPs). LCPs are low dielectric-constant, low loss-tangent [105] materials with very good package hermeticity and a low cost [106]. LCP has gained attention especially as a potential high-performance microwave substrate and packaging material for multilayer array sand for highly integrated circuits [107].

Another interesting solution for multilayer antennas is the usage of low-temperature cofired ceramic (LTCC). This technology allows the implementation of flexible multilayer configurations with a high integration density and many vertical transitions. LTCC multilayer circuits are produced by firing in a single laminate multiple tape layers where conductive, dielectric and/or resistive pastes are selectively deposited to form transmission lines, resistors, inductors, and so on [112].Although LTCC is mainly used for microwave integrated circuits, several interesting results have been obtained also for antenna elements[109-113].

5.5   Bandwidth Enhancement Techniques

: Bandwidth enhancement of microstrip antennas is usually required for many practical applications. Bandwidth can be increased by lowering the Q factor of the microstrip antenna. This can be achieved by using thick substrates or by using materials with low relative dielectric constant. In both cases, insurgence of higher order modes should be carefully considered.

Another common bandwidth enhancement technique is to use radiators with multiple contiguous resonances. This method can be implemented by using parasitic stacked patches [115] or through reactive loading by means of shaped slots, notches, cuts, pins or posts. Wide-band can be achieved also at feed level by designing broadband matching networks [116] or by means of reactive feeds such as L-shaped probes [117-119].

Chapter 6

Conclusions

It is well known fact that the use of dielectric and polymer materials in the fabrication of antennas has been done before. Dielectric materials like Alumina (Al_2O_3) have been used for design of microwave antennas. However due to material properties and difficulty in fabrication, it is not suitable for L,C,X and Ku-Band frequencies application between1-15GHz.Polymer materials like nylon, Teflon, polyacetal, Polypropylenes etc, however have shown good gain and radiation characteristics at these frequencies and are easily fabricated with different design structure. The polymer materials considered suitable for microwave antennas should have fairly large dielectric constant and relatively small tan loss factor at these frequencies The use of dielectric materials for improving the radiation patterns of an antenna is well recognized. It has been observed that gain radiation for standard horn rectangular antenna which is in the frequency of 5-20 GHz can be improved by loading dielectric material. A dielectric rod can act as a guide for electromagnetic waves & this property has been utilized in the various designs of antennas. The guiding action is usually imperfect since considerable electromagnetic

power escapes through the walls of dielectric rod and is radiated from its surface. This tendency of dielectric to radiate micro wave frequencies is turned to advantage in the design of dielectric rod antenna of various types, namely circular rectangular &tapered version of the same, so as to collimate the electromagnetic radiation in a particular direction. For a given polymer the rod diameter determines the wave velocity v, and the gain is optimized when v, and the antenna length l satisfies the Hansen-Woodyard condition. It has been established that polyrod realizes maximum directive gain when

$$d = \frac{\lambda_0}{\sqrt{A\pi(\epsilon_r - 1)}} \qquad (6.1)$$

Where A is the constant to be determined for a polymer at the free-space wave length. Typical values of A for Perspex ($\epsilon_r = 2.56$) and Teflon ($\epsilon_r = 2.1$) at 10.0 GHZ are 1.51 and 1.15 respectively. Since $d \propto \frac{1}{\sqrt{\epsilon_r}}$, it follows that a large dielectric constant r results in the small diameter of the antenna. This is not desirable particularly in operating conditions subjected to shock, vibration and high ambient temperature. Studies show that dielectric constant ϵ_r values in the range $1.5 - 3.0$ are suitable for microwave antenna. Polymers with these ϵ_r values are Teflon, polystyrene, Perspex, nylon, polypropylene and polyacetal. For wide frequency operation the dielectric constant should not vary by in the frequency spectrum at which the application is desired. The gain of the antenna is also affected by the length and the tanloss of the polyrod. It has been observed that antenna length between 6-8 wavelengths realizes optimum gain and small beam-width. The antenna attenuation of microwave power inside the polymer is related to l, dielectric constant ϵ_r and tanloss factor by the expression,

$$\alpha = (\frac{27.3}{\lambda_0})\sqrt{\epsilon_r}.tan\delta \qquad dB/cm. \qquad (6.2)$$

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To minimize attenuation it thus becomes necessary to select a polymer with small dielectric constant ϵ_r and tanloss, and also the antenna length. A 6.5 wavelength long antenna using a polymer with dielectric constant $\epsilon_r = 2.0$ and tanloss =0.001 attenuates the signal 0.014 dB/cm at 10.0 GHZ. Clearly, antennas with $l = 6 - 8$ wavelengths utilizing polymers with dielectric constant $\epsilon_r 3.0$ and tanloss than 0.001 should be used to minimize the attenuation losses and thereby increase the directive gain of the antenna. It has been observed that Teflon which has a low loss tangent value (tan=0.0004) has very low dielectric loss and Gallium Arsenide which has a high loss tangent value $(tan\delta = 0.006)$ offers a very high dielectric loss as compared to the copper loss. It has been seen that as the dielectric permittivity of the material used for the reflectarray design is increased, the bandwidth decreases. Gallium Arsenide, which has the highest dielectric permittivity ($\epsilon_r = 13$) has the minimum 10% and 20% bandwidths of 84MHz and 126MHz respectively while Teflon which has the lowest dielectric permittivity($\epsilon_r = 2.08$) has the highest 10% and 20%bandwidths of 360 MHz and 540 MHz respectively. . It has been shown that Teflon ($\epsilon_r = 2.08$ and $tan\delta = 0.0004$) has maximum bandwidth performance compared to Gallium Arsenide ($\epsilon_r = 2.08$ and $tan\delta = 0.0004$) which has minimum value of the bandwidth measured at different levels of the reflection loss curve. Thus from all this we conclude that the polymer materials considered suitable for microwave antennas should have dielectric constant between 1.5 to 3.0 and relatively small tan loss factor (0.001) at these frequencies.

6.1 Future Plan

In future we will be studying different types of dielectric and polymer materials in depth and applying them on parabolic antenna in order to study various parameters of the parabolic antenna as has been done before on Horn antenna.

Bibliography

[1] K. K.S Jamwal & G. B. Vakil "Dielectric and polymer material properties & characteristics for microwave antenna applications," Ultra science journal vol. 2, pp. 717-719, 2009.

[2] G. B. Vakil & S. Masood Dielectric loaded horn antennas and their gain radiation characteristics Ultra Science vol. 22 pp 409-412 2010.

[3] K.K.S jamwal & R. Vakil , Microwave J (USA),28,9 1985.

[4] K. K. S. Jamwal & A. Dhar, Polymer Bulletin (Germany), 3, 641-644 1980.

[5] J. D. Kraus Antennas.MCG.

[6] K.K.S Jamwal & Atula Dhar, Design of high electric gain polymer rectangular antenna in X-band, India journal of radio & space physics,vol.10,pp115-117 June 1981.

[7] K.K.S Jamwal, Characteristics & design of high gain dielectric circular antenna operated in X-band Helical antennas, IGRSP vol.2 June 1982.

[8] Jamwal & Vakil R,Design analysis of X-band micro wave helical antennas, IJRSP 1984.

[9] K.K.S Jamwal & Vakil R, Design analysis of gain optimized Helix antenna for X-band frequencies Micro wave Journal January 1985.

[10] K.K.S Jamwal & Atul Dhar, Polymer properties of high gain dielectric antennas in X-band, polymer bulletin, springer verlag, vol.3, pp641-644 Dec.1980.

[11] B. Toland, C Liu, P.G. Ingerson,Design and analysis of arbitrarily shaped dielectric antenna, Microwave journal, May 1997,pp278-286

[12] C.A. Balanis, Antenna Theory Analysis and Design, New York: John Wiley & Sons, Inc., 2005; C.A. Balanis, Modern Antenna Handbook, New York: John Wiley & Sons, Inc.2008.

[13] S. Drabowitch, A. Papiernik, H. D. Griffiths, and J. Encinas, Modern Antennas, 2nd edition,NewYork: Springer, 2005.

[14] J. de Kraus and R.J.Marhefka. Antenna for All Application, 3rd edition, New York: McGraw-Hill Science/Engineering/Math, 2001.

[15] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, New York: John Wiley & Sons, Inc.1981.

[16] H .Yagi, Beam transmission of ultra-shortwaves, Proceedings of the IRE, vol. 16, pp. 715740, June 1928.

[17] S. Uda, "Radiotelegraphy and radiotelephony on half-meter waves". Proceedings of the IRE, vol. 18, pp. 1047-1063, June 1930.

[18] Bevilaqua, Peter (2009). "Horn antenna - Introduction".

[19] Poole, Ian. "Horn antenna".

[20] Narayan, C.P. (2007). Antennas And Propagation. Technical Publications. pp.159.

[21] Rodriguez, Vincente (2010). "A brief history of horns".

[22] Emerson, D. T. (December 1997). "The work of Jagadis Chandra Bose: 100 years of MM-wave research". IEEE Transactions on Microwave Theory and Research (IEEE) 45 (12): 2267-2273.

[23] A. David Olver, (1994). Microwave horns and feeds. USA: IET. pp.2-4.

[24] "Welcome to antennas 101" by L. E. Frenzel, "Electronic Design" 2008

[25] R. Bancroft, Microstrip and Printed Antenna Design Noble Publishing 2004, chapter 2-3

[26] Y.T. Lo, D. Solomon and W.F. Richards, "Theory and Experiment on Microstrip Antennas," IEEE Transactions on Antennas and Propagation, AP-27, 1979 pp. 137-149.

[27] R. Dean, Straw Ed. (2000). The ARRL Antenna Book, 19th Ed. USA: American Radio Relay League. pp. 19.15.

[28] Lehpamer, Harvey (2010). Microwave transmission networks: Planning, Design, and Deployment. USA: McGraw Hill Professional. pp. 268-272.

[29] A. David Olver (1994) Microwave Horns and Feeds, p. 61-62

[30] R. Dean, Straw Ed. (2000). The ARRL Antenna Book, 19th Ed.. USA: American Radio Relay League. pp. 18.14

[31] R. Harry, Anderson (2003). Fixed broadband wireless system design. USA: John Wiley & Sons. pp. 206-207.

[32] Pattan, Bruno (1993). Satellite systems: principles and technologies. USA: Springer. pp.267.

[33] Minoli, Daniel (2009). Satellite Systems Engineering in an IPv6 Environment. USA: CRC Press. pp.78.

[34] Quote from Encyclopaedia Britannica: "Dielectric, insulating material or a very poor conductor of electric current. When dielectrics are placed in an electric field, practically no current flows in them because, unlike metals, they have no loosely bound, or free, electrons that may drift through the material". "Dielectrics (physics)". Britannica. 2009. pp.1.

[35] R. von Hippel, Dielectric Materials and Applications, stated: "Dielectrics... are not a narrow class of so-called insulators, but the broad expanse of nonmetals considered from the standpoint of their interaction with electric, magnetic, or electromagnetic fields. Thus we are concerned with gases as well as with liquids and solids, and with the storage of electric and magnetic energy as well as its dissipation." (Technology Press of MIT and John Wiley, NY, 1954).

[36] J. Daintith (1994). Biographical Encyclopedia of Scientists. CRC Press. p.943.

[37] P. Debye (1913), Ver. Deut. Phys. Gesell. 15, 777; reprinted 1954 in collected papers of Peter J.W. Debye Interscience, New York

[38] Mussig & Hans-Joachim, "Semiconductor capacitor with praseodymium oxide as dielectric", published 2003-11-06, issued 2004-10-18, as-

signed to IHP GmbH- Innovations for High Performance Microelectronics/Institute Fur Innovative Mikroelektronik

[39] S. E. Braslavsky, (2007). "Glossary of terms used in photochemistry (IUPAC recommendations 2006)". Pure and Applied Chemistry 79: 293-465.

[40] IEEE Standards Board (1997). "IEEE Standard Definitions of Terms for Radio Wave Propagation". p. 6.

[41] King, Ronold W. P. (1963). Fundamental Electromagnetic Theory. New York: Dover. p.139.

[42] J. D. Jackson (1998). Classical Electrodynamics (Third ed.). New York: Wiley. p.154.

[43] G. A. Mourou, (2006). "Optics in the relativistic regime". Reviews of Modern Physics 78: 309. Bibcode 2006RvMP...78.309M. doi:10.1103/RevModPhys.78.309.

[44] S. Ramo, J.R. Whinnery, and T. Van Duzer, Fields and Waves in Communication Electronics, 3rd ed., (John Wiley and Sons, New York, 1994).

[45] Y. Roiter, S. Minko, (2005). "AFM Single Molecule Experiments at the Solid-Liquid Interface: In Situ Conformation of Adsorbed Flexible Polyelectrolyte Chains". Journal of the American Chemical Society 127 (45): 15688-15689.

[46] Painter, Paul C.; Coleman, Michael M. (1997). Fundamentals of polymer science: an introductory text. Lancaster, Pa.: Technomic Pub. Co. p.1.

[47] N. G. McCrum, C. P. Buckley, C. B. Bucknall, (1997). Principles of polymer engineering. Oxford; New York: Oxford University Press. p.1.

[48] S.A. Baeurle (2009). "Multiscale modeling of polymer materials using field-theoretic methodologies: a survey about recent developments". Journal of Mathematical Chemistry 46 (2): 363-426.

[49] De Gennes, Pierre Gilles (1979). Scaling concepts in polymer physics. Ithaca, N.Y.: Cornell University Press.

[50] Rubinstein, Michael; Ralph H. Colby, (2003). Polymer physics. Oxford; New York: Oxford University Press. p. 5

[51] N. G. McCrum, C. P. Buckley, C. B. Bucknall, (1997). Principles of polymer engineering. Oxford; New York: Oxford University Press. p. 37.

[52] N. G. McCrum, C. P. Buckley, C. B. Bucknall, (1997). Principles of polymer engineering. Oxford; New York: Oxford University Press. p. 30.

[53] Rubinstein, Michael; Ralph H. Colby, (2003). Polymer physics. Oxford; New York: Oxford University Press., p. 3

[54] N. G. McCrum, C. P. Buckley, C. B. Bucknall, (1997). Principles of polymer engineering. Oxford; New York: Oxford University Press. p. 33.

[55] Rubinstein, Michael; Ralph H. Colby, (2003). Polymer physics. Oxford; New York: Oxford University Press. pp. 23-24

[56] Paul C. Painter,; Coleman, Michael M. (1997). Fundamentals of polymer science: an introductory text. Lancaster, Pa.: Technomic Pub. Co p. 22

[57] Rubinstein, Michael; Ralph H. Colby, (2003). Polymer physics. Oxford; New York: Oxford University Press. p. 50

[58] Ashby, Michael; Jones, David (1996). Engineering Materials (2 ed.). Butterworth-Heinermann. pp. 191-195.

[59] M. A. Meyers, K. K. Chawla, (1999). Mechanical Behavior of Materials. Cambridge University Press. p.41.

[60] V. R. Gowariker, N. V. Viswanathan, and Jayadev Sreedhar, Polymer Science, New Age International (P) Limited publishers, Bangalore, 2001

[61] C. A. Harper, Handbook of Plastics Elastomers and Composites, Third Edition, McGraw-Hill Professional Book Group, New York, 1996.

[62] W. D. Callister, Jr, Materials Science and Engineering An introduction, sixth edition, John Wiley & Sons, Inc. 2004.

[63] K. K. S. JAMWAL,: IEEE Trans. Mic. Theory Tech. Conf. 12, New Delhi, (Oct. 1977)

[64] K. K. S. JAMWAL and A. DHAR,: IEEE Trans. Antennas prop.

[65] K. K. S. JAMWAL and A. DHAR,: Rev. Sci. Instrum.

[66] Y. SHIAU: IEEE Trans. Mic. Theory. Tech., MTT-24, 11, 797, (1976).

[67] C. H. WALTER,: Travelling Wave Antennas, New York. N.Y. Dover 1965.

[68] G. J. Wheeler, Introduction to Microwaves, Printince Hall, ING, 1972.

[69] K. K. S. JAMWAL and A. DHAR, Polymer properties of High Gain dielectric Antennas in X-Band, polymer Bulletin, Springer Verlag, Vol. 3, pp 641-644, DEC1980.

[70] K. K. S. JAMWAL and A. DHAR, Impedance Characteristics of polymer circular and rectangular Antennas operated in X-Band, Indian journal of Radio and Space Physics, Vol. 10, pp182-185, oct,1981.

[71] K. K. S. JAMWAL and A. DHAR, Design of High dielectric gain polymer rectangular Antenna in X-Band, Indian Journal of Radio and Space physics, Vol.10, pp 115-117, June 1981.

[72] E. C. Jordans, and K. G. Balmain, Electromagnetic waves and radiating systems, Prentice Hall, ING 1976.

[73] W. L. Weeks, Antenna engineering, Tata McGraw-Hill publishing Co.Ltd, New Delhi 1978.

[74] P. J. Clarricoats, Antenna employing conical di-electric Horns, Proc. I. E. E, Vol. 120, pp 741-749, Jul. 1973.

[75] K. K. S. JAMWAL and R. Vakil, Design Analysis of X-Band Microwave Helical Antenna, I. J. R. S. P, pp 63-65, Vol. 15, April 1986.

[76] K. K. S. JAMWAL and R. Vakil, Design Analysis of Gain Optimized Helix Antenna for X-Band frequencies, Microwave Journal 28. 9. 177-180, Sept.1983.

[77] F. K, Goward, An improvement in end-fire Arrays, Journal IEEE 94 part 3rd pp 415, 1974.

[78] E. F. Harris, Helical Antennas, Antennas Engineering Hand Book, H. Jasik, New York, McGraw-Hill, 1961, chapter 7.

[79] K. K. S. JAMWAL, Di-electric loaded Horn Antennas Characteristics, IEEE Microwave Transmission, CUSAT, Cochin, Dec 1992.

[80] H. Nakano, J. Yamauch, H. Mimaki, Tapered Balanced Helices Radiating in the Axial Mode, Ap 18 IEEE Antennas and Propagation, Digest, 1980.

[81] K. K. S. JAMWAL, Gain radiation Characteristics of tapered X-Band Helical Antennas, INST. Elect. IE (T). ET-67, pp 39-41, NOV. 1987.

[82] K. K. S. JAMWAL, Characteristics and design of high gain dielectric circular antennas operated in X-band, IJRSP, Vol. 11, June 1982.

[83] K. K. S. JAMWAL, Design analysis of X-band Helical Antennas, IJRPS, Vol. 15, pp 63-65, April 1986.

[84] J.Huang (February 15, 1995).Analysis of microstrip reflectarray antenna for microspacecraft application. Spacecraft Telecommunications Equipment section, TDA Progress report 42-12.

[85] D. M. Pozar, D. Targoski and H.D. Syrigos. (February, 1997). Design of millimeter wave microstrip reflectarrays. IEEE Transactions on Antennas propogation, vol. 45.

107

[86] John Huang and Jose Encinar. (2007). Reflectarray Antennas. Wiley, interscience.

[87] M.E.Biallowski and Jose Encinar. (2007). Reflectarray: Potential and challenges. IEEE.

[88] K.Y.SZE and L. Shafal. (1998). Analysis of phase variation due to varying patch length in a microstrip reflectarray.IEEE.

[89] M.Y.Ismail and M.Inam. (2009). Numerical analysis and equivalent circuit modeling for loss quantification of reflectarrays using different substrate materials. IEEE International Conference on Antennas, Propagation and Systems (INAS 2009) Johor, Malaysia.

[90] Harish Rajagopalan and Yahya Rahmat Samii. (April, 2008). Dielectric and Conductor Loss Quantification for MicroStrip Reflectarrays: Simulation and Measurements. IEEE Transactions on Antenna and Propogation, Vol56, no 4.

[91] S. Nishigaki, H. Kato, S. Yano, and R. Kamimura, Microwave Dielectric Properties of $(Ba, Sr)O - Sm_2O_3 - TiO_2$ Ceramics, Am. Ceram. Soc. Bull., 66 [9]1405-10 (1987).

[92] K. Wakino, K. Minai, and H. Tamura, Microwave Characteristics of $(Zr, Sn)TiO_4$ and $BaOPbO - Nd_2O_3TiO_2$ Dielectric Resonators, J. Am. Ceram.Soc., 67 [4] 278-81 (1984).

[93] T. Kakada, S. F. Wang, S. Yoshikawa, S. J. Jang, and R. E. Newnham, Effect of Glass Additions on $BaOTiO_2WO_3$ Microwave Ceramics, J. Am. Ceram.Soc., 77 [7] 1909-16 (1994).

[94] T. Kakada, S. F. Wang, S. Yoshikawa, S. J. Yang, and R. E. Newnham, Effects of Glass Additions on $(Zr, Sn)TiO_4$ for Microwave Applications, J. Am.Ceram. Soc., 77 [9] 2485-8 (1994).

[95] S. I. Hlrano, T. Hayashi, and A. Hattori, Chemical Processing and Microwave Characteristics of $(Zr, Sn)TiO_4$ Microwave Dielectrics, J. Am. Ceram. Soc.,74 [6] 1320-4 (1991).

[96] V. Tolmer and G. Desqardin, Low-Temperature Sintering and Influence of the Process on the Dielectric Properties of $Ba(Zn_{1/3}Ta_{2/3})O_3$, J. Am. Ceram. Soc.,80 [8] 1981-91 (1997).

[97] N. M. Alford and S. J. Penn, Sintered Alumina with Low Dielectric Loss,J. Appl. Phys., 80 [10] 5895-8 (1996).

[98] C. L. Huang, J. J. Wang, and C. Y. Huang, Sintering Behavior and Microwave Dielectric Properties of Nano Alpha-Alumina, Mater. Lett., 59, 3746-9 (2005).

[99] Y. Ohishi, Y. Miyauchi, H. Ohsato, and K. I. Kakimoto, Controlled Temperature Coefficient of Resonant Frequency of $Al_2O_3TiO_2$ Ceramics by AnnealingTreatment, Jpn. J. Appl. Phys., 43 [6A] L749-51 (2004).

[100] Y. Miyauchi, Y. Ohishi, S. Miyake, and H. Ohsato, Improvement of the Dielectric Properties of Rutile-Doped Al2O3 Ceramics by Annealing Treatment,J. Eur. Ceram. Soc., 26, 2093-6 (2006).

[101] A. Templeton, X. Wang, S. J. Penn, S. J. Webb, L. F. Cohen, and N. M.Alford, Microwave Dielectric Loss of Titanium Oxide, J. Am. Ceram. Soc., 83[1] 95-100 (2000).

[102] J. W. Choi, S. J. Yoon, H. J. Kim, and K. H. Yoon, Microwave Dielectric Characteristics of $(1-x)(Al_{1/2}Ta_{1/2})O_{2x}TiO_2$ Ceramics, Jpn. J. Appl. Phys., 41[6A] 3804-7 (2002).

[103] W. C. Tzou, Y. C. Chen, S. L. Chang, and C. F. Yang, Microwave Dielectric Characteristics of Glass-Added $(1-x)Al_2O_{3x}TiO_2$ Ceramics, Jpn. J. Appl. Phys.,41 [12] 7422-5 (2002).

[104] DeJean, G., Bairavasubramanian, R., Thompson, D. et al. (2005) Liquid crystal polymer (LCP): a new organic material for the development of multilayer dual-frequency/dual-polarization flexible antenna arrays. Antennas and Wireless Propagation Letters, 4(1), 2225.

[105] Jayaraj, K., Noll, T.E. and Singh, D. (1995) RF characterization of a low cost multichip packaging technology for monolithic microwave and millimeter wave integrated circuits. Proceedings of the URSI International Symposium on Signals, Systems, and Electronics, ISSSE95, pp. 443-446.

[106] Farrell, B. and St Lawrence, M. (2002) The processing of liquid crystalline polymer printed circuits. Proceedings of the 52nd Electronic Components and Technology Conference, pp. 667-671.

[107] Brownlee, K., Raj, P.M., Bhattacharya, S.K. et al. (2002) Evaluation of liquid crystal polymers for high performance SOP application. Proceedings of the 52nd Electronic Components and Technology Conference, pp. 676-680.

[108] Y. Imanaka, (2010) Multilayered Low Temperature Cofired Ceramics (LTCC) Technology, Soft cover reprint of hardcover 1st edn, 2005, Springer.

[109] Wi, S.-H., Zhang, Y.P., Kim, H. et al. (2011) Integration of antenna and feeding network for compact UWB transceiver package. IEEE Transactions on Components, Packaging and Manufacturing Technology, 1(1), 111-118.

[110] Seki, T., Honma, N., Nishikawa, K. and Tsunekawa, K. (2005) A 60-GHz multilayer parasitic microstrip array antenna on LTCC substrate for system-on-package. IEEE Microwave and Wireless Components Letters, 15(5), 339-341.

[111] Wi, S.-H., Kim, J.-S., Kang, N.-K. et al. (2007) Package-level integrated LTCC antenna for RF package application.IEEE Transactions on Advanced Packaging, 30(1), 132-141.

[112] Chen, S.C., Liu, G.C., Chen, X.Y. et al. (2010) Compact dual-band GPS microstrip antenna using multilayer LTCC substrate. IEEE Antennas and Wireless Propagation Letters, 9, 421-423.

[113] Sanadgol, B., Holzwarth, S., Milano, A. and Popovich,R. (2010) 60GHz substrate integrated waveguide fed steerable LTCC antenna array. Proceedings of the Fourth European Conference on Antennas and Propagation (EuCAP), pp. 1-4.

[114] Chiba, T., Suzuki, Y. and Miyano, N. (1982) Suppression of higher modes and cross polarized component for microstrip antennas. Antennas and Propagation Society International Symposium, vol. 20, pp. 285-288.

[115] F. Croq and D.M. Pozar, (1991) Millimeter-wave design of wide-band aperture-coupled stacked microstrip antennas. IEEE Transactions on Antennas and Propagation, 39(12), 1770-1776.

[116] H. F. Pues and Van de Capelle, A.R. (1989) An impedance-matching technique for increasing the bandwidth of microstrip antennas. IEEE Transactions on Antennas and Propagation, 37(11), 1345-1354.

[117] Park, J., Na, H.-G., and S.-H. Baik, (2004) Design of a modified L-probe fed microstrip patch antenna. IEEE Antennas and Wireless Propagation Letters, 3(1), 117-119.

[118] Guo,Y.-X., Chia, M.Y., Chen, Z.N. and Luk, K.-M. (2004)Wide-band L-probe fed circular patch antenna for conical pattern radiation. IEEE Transactions on Antennas and Propagation, 52(4), 1115-1116.

[119] Mak, C.L., Luk, K.M., Lee, K.F. and Chow, Y.L. (2000) Experimental study of a microstrip patch antenna with an L-shaped probe. IEEE Transactions on Antennas and Propagation, 48(5), 777-783.