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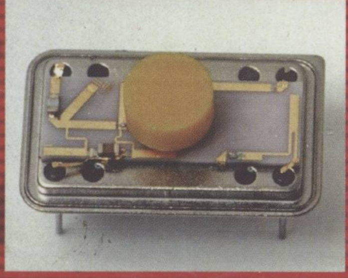
Dielectric Materials for Wireless Communication



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DIELECTRIC MATERIALS FOR WIRELESS COMMUNICATION

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Foreword

In this book Dr. Sebastian describes the current state of the art of what are now broadly described as microwave dielectric materials. The history of these materials stretches back to the late 19th century. In 1897 Lord Rayleigh described a dielectric waveguide and in 1909 Debye described dielectric spheres. It was not until 1939 that Richtmyer coined the term "Dielectric Resonator" when he suggested that a dielectric ring could confine high-frequency electromagnetic waves and hence form a resonator. Richtmyer also realized that an open resonator would resonate into free space and three quarters of a century later these ideas have spawned a multibillion dielectric antenna industry and dielectric resonator industry. Astonishingly, our lives have been completely transformed by the science of a handful of people.

Today, microwave dielectric materials are all-pervasive. Several people buy a new mobile phone every second of every day of every year. This book takes us to the heart of the science and it takes us through the science in a comprehensive manner. We learn about the key properties of relative permittivity, of dielectric loss and of temperature coefficients and we learn how the microstructure and chemistry of the dielectric is crucial in determining the key properties. We learn about the beginnings of the now huge dielectric resonator industry in the pioneering work of Hank O'Brian and Taki Negas on barium titanate compositions. Historically the book is faithful and we next learn about the zirconium titanates, finally ending up with the newer perovskites.

The amazingly forgiving properties of the perovskites, in terms of substitution, are described and the ability of these substitutions to affect all the key properties – the temperature coefficient, the dielectric loss and the relative dielectric constant. The book describes how one can tailor the dielectric properties of materials by judicious choice of substituent or dopant.

In the final chapters we see interesting information of specific materials such as titania and alumina as well as low sintering temperature materials that can be cofired with electrodes such as silver. Included in an appendix is the most comprehensive list of microwave dielectric materials, along with their key properties, that exists.

This book will serve a wide range of communities – from University students and tutors to industrial laboratories. The volume of information available is prodigious as a rapid glance of the contents indicates and this in combination with a truly comprehensive list of over a thousand references makes this book a most valuable source of information. Dr. Sebastian has worked in the area of microwave dielectrics for many years and has published extensively in this area. This book is a considerable achievement.

Professor Neil McN Alford FREng
Imperial College London

Acknowledgment

The subject matter presented in this book has been derived from several publications in addition to our own and I am grateful to many authors and publishers for allowing us to use their material. I am indebted to my doctoral students and postdoctoral fellows whose researches in this area immensely helped me to write this book. I am grateful to Dr. Tamura, Murata Manufacturing Company in Japan and Nokia in Finland for permitting me to use their images in the cover page of this book. I wish to thank Prof. Jerzy Krupka, Prof. Stanislav Kamba, Prof. Heli Jantunnen, Prof. Neil Alford, Prof. Hitoshi Ohsato, Prof. Roberto Moreira, Prof. P. Mohanan, Prof. V R K Murthy, Dr. R. Ratheesh, Dr. H. Sreemoolanathan and Dr. J. James for critically reading parts of the manuscript and giving useful suggestions. I am also thankful to Prof. T. K. Chandrasekhar, Director NIIST for his encouragement and to Mr. G. Subodh and Sumesh George for drawing some of the figures. I am also grateful to Prof. Neil Alford, Imperial College for writing the Foreword to this book.

M. T. Sebastian

CONTENTS

CHAPTER ONE

INTRODUCTION

Microwave dielectric materials play a key role in global society with a wide range of applications from terrestrial and satellite communication including software radio, GPS, and DBS TV to environmental monitoring via satellites. In order to meet the specifications of the current and future systems, improved or new microwave components based on dedicated dielectric materials and new designs are required. The recent progress in microwave telecommunication, satellite broadcasting and intelligent transport systems (ITS) has resulted in an increasing demand for dielectric resonators (DRs), which are low loss ceramic pucks used mainly in wireless communication devices. With the recent revolution in mobile phone and satellite communication systems using microwaves as the carrier, the research and development in the field of device miniaturization has been one of the biggest challenges in contemporary Materials Science. This revolution is apparent on a daily basis in the ever increasing number of cell phone users. The recent advances in materials development has led to these revolutionary changes in wireless communication technology. Dielectric oxide ceramics have revolutionized the microwave wireless communication industry by reducing the size and cost of filter, oscillator and antenna components in applications ranging from cellular phones to global positioning systems. Wireless communication technology demands materials which have their own specialized requirements and functions. The importance of miniaturization cannot be overemphasized in any hand-held communication application and can be seen in the dramatic decrease in the size and weight of devices such as cell phones in recent years. This constant need for miniaturization provides a continuing driving force for the discovery and development of increasingly sophisticated materials to perform the same or improved function with decreased size and weight.

A DR is an electromagnetic component that exhibits resonance with useful properties for a narrow range of frequencies. The resonance is similar to that of a circular hollow metallic waveguide except for the boundary being defined by a large change in permittivity rather than by a conductor. Dielectric resonators generally consist of a puck of ceramic that has a high permittivity and a low dissipation factor. The resonant frequency is determined by the overall physical dimensions of the puck and the permittivity of the material and its immediate surroundings. The key properties required for a DR are high quality factor (Q), high relative permittivity (ε_r) and near zero temperature coefficient of resonant frequency (τ_f). An optimal DR that satisfies these three properties simultaneously is difficult to achieve in a particular material.

In the early microwave systems, bulk metallic cavities were used as resonators, but were huge and not integrated with microwave integrated circuits (MICs). On the other hand, stripline resonators have a poor quality factor and poor temperature stability resulting in the instability of the circuit. Hence the importance of DRs, which are easily integrated with MICs with low loss and with thermally stable frequency, especially at mm wavelengths. Most of the microwave-based device systems are located in the frequency range

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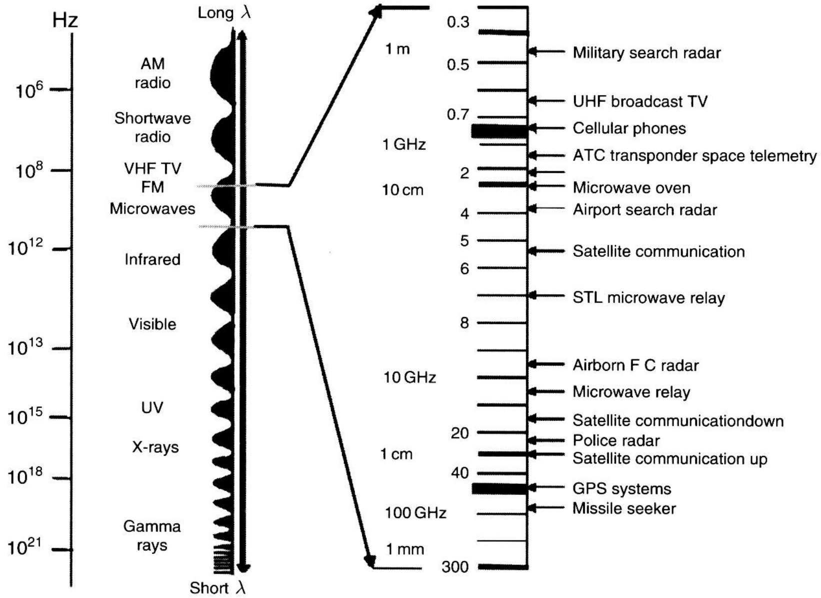

Figure 1.1 Microwave spectrum and applications.

300 MHz–300 GHz as shown in Figure 1.1. Technological improvements in DRs have contributed to considerable advancements in modern wireless communications. Ceramic DRs have the advantage of being more miniaturized as compared to traditional microwave cavities, and have a significantly higher quality factor. DRs have replaced cavity resonators in most microwave and millimeter-wave applications for reasons of cost, dimension, mass, stability, efficiency, tenability, ruggedness and ease of use. In addition, the temperature variation of the resonant frequency of DRs can be engineered to a desired value to meet circuit designer's requirements. Functioning as important components in communication circuits, DRs can create and filter frequencies in oscillators, amplifiers and tuners. In order to respond to the requirement for increased channel capacity in ground-based cellular and satellite communications, new devices with superior performance must be developed. The system performance is closely related to material properties. In microwave communications, DR filters are used to discriminate between wanted and unwanted signal frequencies from the transmitted and received signals. The desired frequency is extracted and detected to maintain a strong signal-to-noise ratio. For clarity, it is also critical that the wanted signal frequencies are not affected by seasonal temperature changes.

The low permittivity ceramics are used for millimeter-wave communication and also as substrates for microwave integrated circuits. The medium ε_r ceramics with permittivity in the range 25–50 are used for satellite communications and in cell phone base stations. The high ε_r materials are used in mobile phones, where miniaturization of the device is very important. For millimeter-wave and substrate application, a temperature-stable low permittivity and high Q (low loss) materials are required for high speed signal transmission with minimum attenuation.

The term "dielectric resonator" first appeared in 1939, when Richtmeyer of Stanford University showed that a suitably shaped dielectric piece can function as a microwave resonator [1]. However, it took more than 20 years to generate further interest on DRs and to test Richtmeyer's prediction experimentally. In 1953, Schlicke [2] reported on super high permittivity materials (~1000 or more) and their applications as capacitors at relatively low RF frequencies. In the early 1960s, Okaya and Barash from Columbia University rediscovered DRs while working on rutile single crystals [3, 4]. Okaya and Barash [3, 4] measured the permittivity and Q of TiO_2 single crystals at room temperature down to 50 K in the microwave frequency range, using the commensurate transmission line technique [4]. Later several authors developed methods for measuring the ε_r, quality factor (Q) and τ_f of DRs. These methods are discussed in Chapter 2. In the early 1960s, Cohen and his co-workers [5] from Rantec Corporation performed the first extensive theoretical and experimental evolution of DR. Rutile ceramics were used for the experiments that had an isotropic permittivity of about 100. The TiO_2 has a poor (+450 ppm/°C) stability of resonant frequency that prevented its commercial exploitation. The first microwave filter using TiO_2 ceramics was proposed by Cohen in 1968 [6, 7]. But this filter was not useful for practical applications because of its high τ_f. A real breakthrough in DR ceramic technology occurred in the early 1970s, when the first temperature-stable, low loss barium tetratitanate ($BaTi_4O_9$) ceramics were developed by Masse et al. [8]. Later, barium nanotitanate ($Ba_2Ti_9O_{20}$) with improved performance was reported by Bell Laboratories [9]. The next breakthrough came from Japan when Murata Manufacturing Company produced $(Zr,Sn)TiO_4$ ceramics [10, 11]. They offered adjustable compositions so that temperature coefficients could be varied between +10 and −10 ppm/°C. Later, in 1975, Wakino et al. realized the miniaturization of the DR-based filters and oscillators [12]. Since then extensive theoretical and experimental work and development of several DR materials has occurred. This early work resulted in the actual use of DRs as microwave components. Commercial production of DRs started in the early 1980s. The number of papers published and patents filed on the science and technology of DRs increased considerably over the years as shown in Figure 1.2. There are about 2300 low loss dielectric materials reported in the literature (see Appendix 2). More than 5000 papers have been published and over 1000 patents were filed on DR materials and devices. However, with only a limited number of useful dielectric ceramic materials to choose from, the electronic industry is constantly searching for new materials that are easily affordable for manufacture.

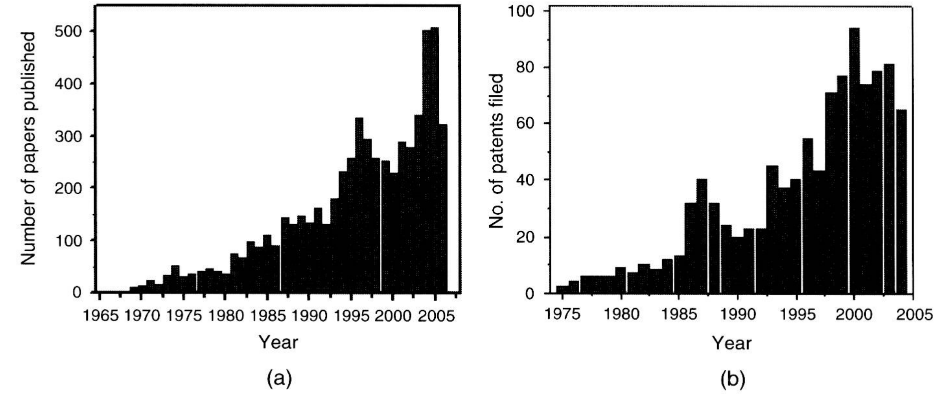

Figure 1.2 (a) The number of papers published on dielectric resonator materials and technology versus year of publishing (b) Number of patents filed versus year.

Richtmeyer [1] in 1939 theoretically predicted that a piece of dielectric with regular geometry and high ε_r can confine electromagnetic energy within itself, but still be prone to energy loss due to radiation. It was found that through total multiple internal reflections, a piece of high ε_r dielectric can confine microwave energy at a few discrete frequencies, provided the energy is fed in the appropriate direction (see Figure 1.3). If the transverse dimensions of the sample are comparable to the wavelength of the microwave, then certain field distributions or modes will satisfy Maxwell's equations and boundary conditions. The reflection coefficient approaches unity as ε_r approaches infinity. In the microwave frequency range, free space wavelength (λ_c) is in centimeters and hence the wavelength (λ_g) inside the dielectric will be in millimeters only when the value of ε_r is in the range 20–100. To get resonance, dimensions of the dielectric must be of the same order (in millimeters). Still larger ε_r gives higher confinement of energy, reduced radiation loss and better miniaturization. However, high ε_r will result in higher dielectric losses because of inherent material properties. When exposed to free space, a DR can also radiate microwave energy when it is fed suitably and can be used as efficient radiators, called Dielectric Resonator Antennas (DRA). A DR with finite values of ε_r prevents 100% reflection from the air/dielectric boundary and hence some field will always exist in the vicinity of the dielectric. This is of great advantage since it enables one to couple microwave power easily to the DR by matching the field pattern of the coupling elements to that of the DR. Figure 1.4 (a) and (b) illustrates the variation of electric and magnetic fields inside a dielectric ($Ca_5Nb_2TiO_{12}$ ceramic puck with $\varepsilon_r = 48$) kept inside a copper cavity and simulated using a three-dimensional transmission line matrix modeling method [13].

The size of a DR is considerably smaller than the size of an empty resonant cavity operating at the same frequency, provided the relative permittivity (ε_r) of the material is

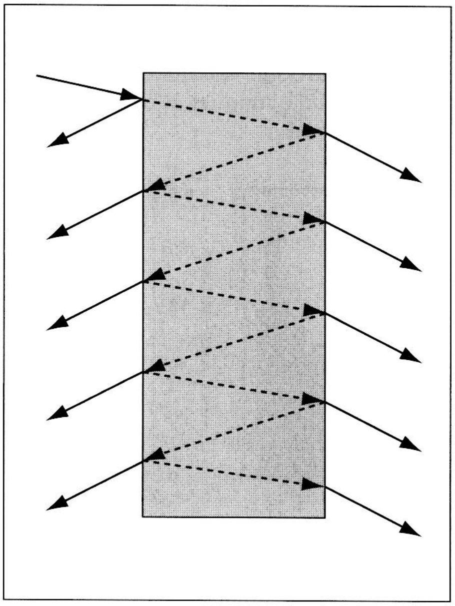

Figure 1.3 Schematic sketch of total multiple internal reflections in a high ε_r dielectric piece.

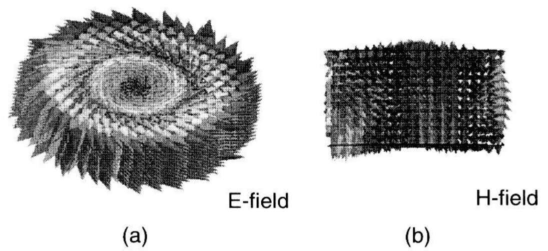

Figure 1.4 Variation of (a) electric and (b) magnetic fields of $TE_{01\delta}$ resonance mode of a $Ca_5Nb_2TiO_{12}$ ceramic resonator with $\varepsilon_r = 48$ (after Ref. [13]) (see Color Plate section).

substantially higher than unity. Higher ε_r shrinks overall circuit/device size proportional to $(1/\varepsilon_r)^{1/2}$. For example, a circuit is compressed by a factor of six when a high Q ceramic with $\varepsilon_r = 36$ is substituted for a high Q air cavity $\varepsilon_r = 1$. The shape of a DR is usually a solid cylinder but can also be tubular, spherical and parallelepiped. Figure 1.5 shows some of the low loss dielectric pucks made at the author's laboratory. A commonly used resonant mode of a cylindrical DR is $TE_{01\delta}$. At resonant frequency, electromagnetic fields inside a resonator store energy equally in electric and magnetic fields. When ε_r is about 40, more than 95% of the stored electric energy and over 60% stored magnetic energy are located within the dielectric cylinder. The remaining energy is distributed in the air around the resonator, decaying rapidly with distance away from the resonator boundary. The DR can be incorporated into a microwave network by exciting it with microstrip transmission lines, as shown in Figure 1.6. The distance between the resonator and the microstrip conductor determines the amount of coupling. In order to prevent losses due to radiation, the entire device is usually enclosed in a metallic shielding box.

High Q minimizes circuit insertion losses and can be used as a highly selective circuit. In addition, high Q suppresses the electrical noise in oscillator devices. Although several manufacturers may produce similar components for the same application, there are subtle differences in circuit design, construction and packaging. Since frequency drift of a device is a consequence of the overall thermal expansion of its unique combination of

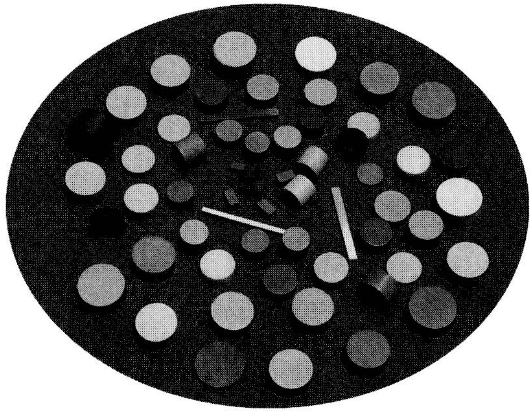

Figure 1.5 Picture of dielectric ceramic packs developed at the author's laboratory (see Color Plate section).

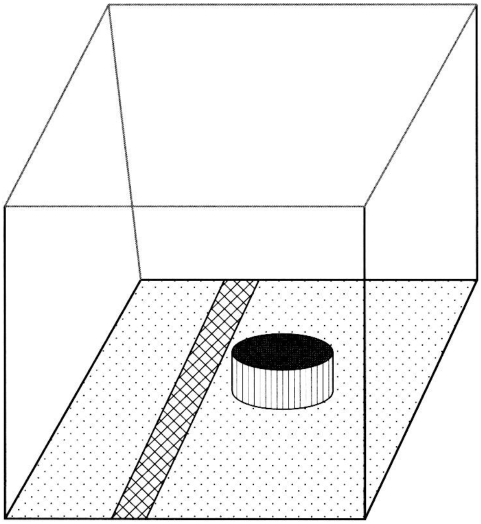

Figure 1.6 Dielectric resonator mounted on a microstrip.

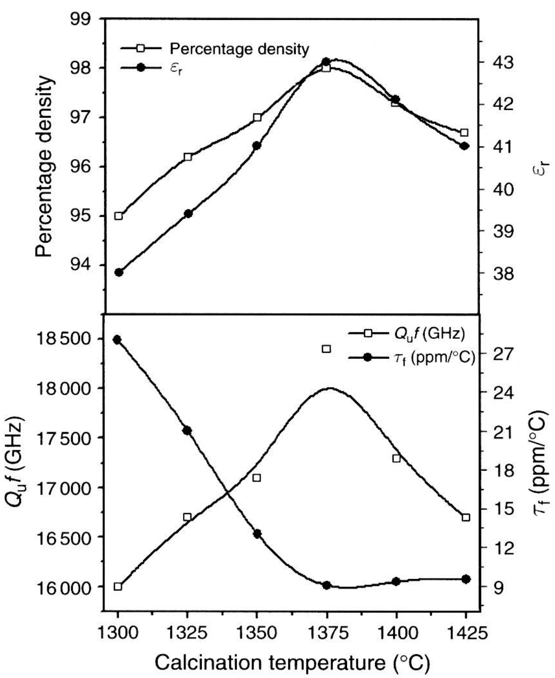

Figure 1.7 The variation of the relative density, ε_r, Qf and τ_f of $Ba(Sm_{1/2}Nb_{1/2})O_3$ ceramic versus calcination temperature. Sintering temperature 1550°C for 2 hours (after Ref. [16]).