Microwave Dielectric Ceramic Materials and Their Industry Development Overview and Future Prospects

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Abstract. Nowadays, microwave dielectric ceramics are widely used in all kinds of modern communication equipment, becoming the key material for manufacturing microwave dielectric filters and resonators. With the rapid development of related fields, the scope of application of microwave dielectric ceramics has been further expanded. On this basis, this paper explores the development history of microwave dielectric ceramics and the situation and future outlook of its industry. By combining historical events and data, the development history of microwave dielectric ceramics is described. The situation is also analysed and discussed in the context of the times and current events to provide an objective evaluation and forecast of the industry. The final results show that in the context of the new era of 5G, the microwave dielectric ceramics industry has entered a brand new stage of development and it presents a huge potential for innovation and development.

1. Introduction
As a new functional ceramic material that has emerged in recent decades, microwave dielectric ceramics are widely used in various types of modern communication equipment, becoming the key material for manufacturing microwave dielectric filters and resonators. Due to its low dielectric loss, small temperature coefficient, high dielectric constant and other performance characteristics, microwave dielectric ceramics can meet the requirements of high reliability, low cost, miniaturization and integration of microwave circuits, and also become one of the key projects of high-tech ceramic research. [1]

Based on the popular trends and widespread use of microwave dielectric ceramics, this thesis focuses on the definition, classification and development history of microwave dielectric ceramics and analyses the development and future prospects of the microwave dielectric ceramics industry. Its development history and classification is described in the context of historical events and times, and its industry is also objectively evaluated and forecast. This thesis concentrates on an overview of the research and development of microwave dielectric ceramics with the aim of deepening the knowledge and understanding of microwave dielectric ceramics and providing a better assessment of its future development trends.

2. Introduction to microwave dielectric ceramics
The birth of microwave dielectric ceramics can be traced back to the 1930s. In the late 1930s, B. Q Richtmyer[2] theoretically proved the possibility of using dielectric in microwave circuits as dielectric resonators; in the late 1960s Cohn[3] and others used TiO2 ceramic materials to design microwave filters; in the early 1970s the United States Bryan and other first developed a BaTi4O9[2] new
microwave ceramic materials with high dielectric constant and high Q value. This series of scientific research progresses opened the curtain on the development of microwave dielectric ceramics. [4]

Microwave dielectric ceramics is a fundamental key material to achieve microwave control functions, as a dielectric material, which plays an important role in dielectric isolation, dielectric waveguide and dielectric resonance in the microwave circuit. And it is the key material for the manufacture of microwave components, widely used in mobile communications, satellite communications and military radar and other fields.

According to the different parameters, microwave dielectric ceramics can be divided into low dielectric constant class microwave dielectric ceramics, medium dielectric constant class microwave dielectric ceramics and high dielectric constant class microwave dielectric ceramics, whose application direction is different.

2.1. Low dielectric constant microwave dielectric ceramics

These ceramics are made from a series of chalcogenide structured materials with a dielectric constant between 25 and 30 and are characterized by high Q and low dielectric loss in the high frequency band.

2.2. Medium permittivity microwave dielectric ceramics

These ceramics are made from BaTi409 and Ba2Ti9020 based materials, which are less costly than other types, have a dielectric constant between 40 and 80 and have good temperature stability at moderate frequencies. They are also suitable for low and high frequencies and are often used in various resonators and filters.

2.3. High dielectric constant class of microwave dielectric ceramics

This type of ceramic is made from a series of lead-based chalcogenide materials with a dielectric constant between 80 and 90. By virtue of its high dielectric constant, low Q value and high mass loss in the low microwave frequency band, this type of ceramic has a strong ability to polarise under the action of an electric field, making it easier to concentrate electromagnetic energy and promoting the miniaturization and integration of microwave equipment, which is widely used in low frequency band communication equipment.

3. Microwave dielectric ceramics development history

Since the feasibility of dielectric ceramic materials for resonators was theoretically proven, the United States took the lead in the development of microwave dielectric ceramic materials, and in the 1970s developed a practical K38 material. Subsequently, France, Germany and other European countries have also begun to research. At present, Japan has taken the lead in this field of research, whose many companies have established a unique system of microwave dielectric materials. With the broadening of the scope of microwave applications and more complex application conditions in special frequency band, the quality of microwave dielectric ceramic materials are increasingly demanding. Now, the research and development of microwave dielectric ceramic materials with $\varepsilon_r \geq 60$ or $\varepsilon_r \leq 30$ has become a hot spot in the field of global materials research. In July 1992, Japan's Matsushita Electric Company developed the wrong lead acid system of materials with $\varepsilon_r \geq 110$, $Q \geq 1200$, $\tau_f \leq 30 \times 10^{-6}$ / °C, which is the highest $\varepsilon_r$ microwave dielectric ceramic materials to date. [5] ~ [6]

China's development of microwave dielectric ceramic materials started late, at the beginning of the 80s, basically repeating and tracking the research work abroad. Due to the low level of materials and processes, testing and evaluation difficulties and other factors, the quality of the developed microwave dielectric ceramics is far from the needs of the development of microwave communication technology in China. However, by 1991, the Ministry of Electronics and the State Science and Technology Commission has strengthened the research work on microwave dielectric ceramic materials. Beijing Institute of Building Materials, the University of Electronic Science and Technology Information Materials Institute and other research units have taken microwave dielectric ceramics as an important subject in "Eighth Five-Year Plan" and "Ninth Five-Year Plan", striving to catch up with the world
level. At present, many independently developed microwave dielectric ceramic materials have reached the international level.

Given the development of microwave dielectric ceramics, it can be broadly divided into four different stages: the 1960s, 1970s, 1980s and 1990s. The focus of research and development and representative materials for each stage are shown in Table 1. From the current development situation, the technology and process of microwave dielectric ceramic materials in the medium frequency band has been quite mature, while in the high frequency band and low frequency band, it is still under development. [7]

Table 1. Overview of the development of microwave dielectric ceramics

| Period of time | Contents | Year | Country or name | Materials | Characteristics |
|---------------|----------|------|----------------|-----------|-----------------|
| 1960s         | Exploration of dielectric oscillator mode materials | 1960 | Cohn | TiO$_2$ | $f$/GHz $Q$ $\varepsilon_r$ $\tau_f/10^{-6} \text{C}^{-1}$ | 4 2000 100 500 |
| 1969          | Proposed method for evaluating microwave dielectric ceramics | 1969 | Hakki |          |                  |
| 1970s         | Microwave ceramics enter the practical phase | 1971 | USA | K38 | 6 $10^5$ 39.7 3 |
| 1974          | | 1974 | USA | BaTi$_6$O$_{20}$ | 7 $10^5$ 37 45 |
| 1979          | | 1979 | Murata | (Zr,Sn)TiO$_4$ | 8 6500 36 ±2 |
| 1980s         | The continuous expansion of new systems of materials | 1982 | USA | BMT | 10 16800 25 4.4 |
| 1982          | | | Panasonic | BST | 2 4000 70 4 |
| 1984          | | | | BZT | 10 5100 30 34 |
| 1985          | | | Hiroshi Ouchi | BNT | 4 2820 78 45 |
| 1990s         | New technologies and materials | 1991 | He Jin | BNT prepared by HIP | 2 2000 84 30 |
| 1992          | | | Panasonic | Pb-Ti-Na-Ba | 2 1200 110 30 |

4. China's microwave dielectric ceramics industry development status

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5. Microwave dielectric ceramics industry development trend and application foresight.
With the further development of communications technology, China is about to enter a new era of 5G, microwave communications industry will usher in new changes and development. At the same time, along with the gradual maturity of the Internet of Things technology, wireless communications equipment demand is growing, which will bring innovation and development to the microwave dielectric ceramic industry. It is expected to show the following three development trends.

5.1. Products towards high frequency, multi-frequency, miniaturization, integration and modularity
Microwave dielectric ceramics are a fundamental component of the communications industry. With the development of 5G communication technology, wireless communication is gradually developing in the direction of high frequency. In this context, microwave dielectric ceramic components with good high-frequency characteristics will have greater development space and application areas. It is expected that through new forming methods, preparation methods and new material systems, the future of the microwave dielectric ceramics industry will reduce the resonant frequency temperature coefficient of low dielectric systems, pursue the limits of ultra-low loss at high frequencies, improve the quality factor of high dielectric systems and explore new materials with higher dielectric constants to achieve the goal of high frequency.

In addition, the microwave communication industry will also become portable, miniaturized, functional and highly reliable products, which means the higher requirements of the microwave dielectric ceramic components' miniaturization, integration, modular. This trend will also become a major driving force in the development of microwave dielectric products.

5.2. 5G industrialization will drive the industry to see explosive growth
As a key component of the communication base station RF unit, mobile communication base stations, dielectric resonators, dielectric filters, duplexer and multiplexer and other equipment is also an important application direction of microwave dielectric ceramic components. 5G commercialization brings a huge market space that will make the microwave dielectric ceramic industry in the upstream end of the 5G industry chain show explosive growth.

5.2.1. 5G communication technology is improving and the number of base stations is increasing significantly. According to the data from the Ministry of Industry and Information Technology, the 5G band resources allocated by China's three major operators are concentrated in the 3.5GHz-4.9GHz range (The details are shown in Table 2). The expansion of frequency and the increase in frequency efficiency also lead to a shorter single carrier wavelength, thus reducing the signal coverage from 300m-500m to 20m-50m, which determines a significant increase in the number of micro base stations. In order to achieve ultra-dense networking, the number of 5G base stations will be 4-5 times that of the 4G era, and the overall increase in the number of base stations will drive a significant increase in the number of upstream microwave communication components closely related to microwave dielectric ceramics.
Table 2. 5G spectrum resources for China's three major operators, 2019

| Communication operators | 5G Spectrum Resources       |
|-------------------------|----------------------------|
| China Mobile            | 2.5GHz–2.6GHz, 4.8GHz–4.9GHz|
| China Unicom            | 3.5GHz–3.6GHz               |
| China Telecom           | 3.4GHz–3.5GHz               |

5.2.2. Thanks to the demand of 5G antenna miniaturization, microwave dielectric ceramic components will become the mainstream solution. Firstly, the number of antenna channels will increase: China's 5G band will be dominated by 3.5GHz-4.9GHz and will use Massive MIMO technology. As a result, the number of channels of 5G antennas will increase by 7-15 times; secondly, the antennas will become active: in 5G base stations, the RF unit RRU and antennas will be combined into a new AAU active antenna unit. This not only enhances coverage and reduces feedline losses, but also allows for multi-band and multi-standard networking, saving resources and costs. Due to the increase in the number of antenna channels and the development of active antennas, miniaturization and lightweight are inevitably the future of antenna design. Under the condition of satisfying the performance, ceramic dielectric waveguide filter, which can make the antenna equipment smaller and lighter, will stand out and become the mainstream technology solution for 5G base stations.

5.2.3. 5G planning layout contains a vast market space, leading to the rapid expansion of the industrial scale. Based on the management system for mobile communications, the Chinese government's 5G plan will directly affect the scale of investment and development direction of mobile communications. At present, China has a number of provinces and cities that have released 5G industry action plan, for the 5G industry chain manufacturers to provide clear industrial development goals, its development goals must be the breakthrough and development of 5G upstream RF components, active array antennas and other key technologies and core components, which will drive the rapid development of microwave dielectric ceramic components, the industry market scale will be rapidly expanded under the policy support in all aspects.

5.3. The scope of application of microwave dielectric ceramics based on the Internet of Things technology will be continuously expanded. The implementation of the Internet of Things requires a three-layer architecture of the sensing layer, network layer, platform layer and sensing layer. Among them, the wireless module in the sensing layer is the key device to realize all kinds of objects to access the network and locate them, which has a great demand for microwave dielectric ceramics. For example, LTCC microwave dielectric ceramic components can be widely used in IoT wireless modules based on their miniaturization and integration characteristics. Coupled with the vast intelligent terminal coverage of the Internet of Things, a large number of wireless modules will be put into use, which can certainly drive the rapid development of microwave dielectric ceramic components industry. Take the smart home as an example, its indoor distribution system can cover more than 90% of different types of microwave dielectric ceramic products, such as single and dual-mode dielectric antenna, SMD dielectric antenna, dielectric filter, dielectric waveguide filter and so on.

At the same time, the microwave dielectric ceramics application range is also expanding. With the continuous maturity of IoT intelligent technology, IoT applications will continue to expand, whether it is the field of system integration application services or IoT intelligent terminal field, there will be huge room for improvement, and eventually, the application of microwave dielectric ceramics will also be expanded. The expanding application scenarios of the Internet of Things will become an important direction to tap the growth potential of the microwave dielectric ceramics field.
Public services: smart municipalities (gas, water, heat), smart campuses, smart transportation (drones, drones, etc.), smart environmental protection.

Vertical industries: Industrial IoT networking (industrial robots, industrial wearables), smart logistics, smart hospitals, smart agriculture.

Systematic and integrated application services

Internet of Things

Meters: intelligent water meters, intelligent gas meters, industrial monitoring and detection meters, etc.

Monitoring category: Industrial equipment and public service testing equipment.

In-car category: In-car front loading category.

Scheduling classes: intelligent ports, customs, warehouse storage management, cold chain logistics

Wearable devices: sports and fitness, home care, etc.

Consumer electronics: smart watches, smart autos, smart helmets, etc.

6. Conclusion

With the continuous development of microwave technology, the scope of application of microwave dielectric ceramics continues to be broadened, the performance and quality of microwave ceramic materials are also put forward higher requirements. In such a development trend, the research and development of microwave dielectric ceramic materials will be further emphasized and deepened. In addition, with the popularity of 5G, Internet of Things, the market demand for microwave dielectric ceramics is also gradually rising, which will guide the rapid development of microwave dielectric ceramics industry, and bring many opportunities for development and great expansion space.

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