A CRITICAL REVIEW ON THE FABRICATION PROCESSES AND APPLICATIONS OF MICROWAVE DIELECTRIC CERAMICS $Ba_{6-3x}Nd_{8+2x}Ti_{18}O_{54}$

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ABSTRACT

Microwave dielectric ceramics with the compositional formula of $Ba_{6-3x}Nd_{8+2x}Ti_{18}O_{54}$ (BNT) are attracted material researchers interests due to their wide applications in many areas as mobile and satellite communication systems, antennas, oscillators, filters, wireless communications, and sensors. BNT ceramics are Neodymium modified Barium Titanate materials that have very well in dielectric properties. The excellent properties of BNT ceramics included high dielectric constant, high quality factor, and small temperature coefficient frequency. With these superior advantageous features, this material can be used in various applications. According to review of relevant literature, it has been noticed that BNT ceramics can be prepared by different synthesis techniques and give different information on structural and electrical properties. The fantastic properties of BNT ceramics make them suitable for implementing in difference applications. In antenna field, BNT ceramics are used for dielectric resonator antenna. BNT ceramic also has the potential to replace traditional microstrip line filter as dielectric filter. BNT ceramic is highly useful material for microwave signal source like dielectric oscillator. It finds applications in portable telephone, digital broadcasting, and multilayer capacitors. This material also can be used in satellite communication systems. Therefore, this current review focuses on different technique for synthesis of BNT ceramics in literature, their characterization methods, influence of doping on the properties of BNT ceramics and their applications will be discussed.

KEYWORDS: $Ba_{6-3x}Nd_{8+2x}Ti_{18}O_{54}$, Microwave Dielectric Ceramics, Synthesis, Dielectric Properties, Dielectric Resonator & Dielectric Filter

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1. INTRODUCTION

Microwave dielectric ceramics (Goulas *et al*, 2020; Wang *et al*, 2020; Xiang *et al*, 2020) could be considered as highly significant electronic materials that have been extremely investigated for the enhancement on their performances and functionalities in several areas and applications in science, technologies, and engineering. The applications involve from terrestrial and satellite communication like software radio (Becker *et al*, 2020; Mansour *et al*, 2019; Roy *et al*, 2020; Zhang *et al*, 2018; Zhong *et al*, 2018), GPS (Abdolkarimi *et al*, 2020; Katapally *et al*, 2020; Kudłacik *et al*, 2021; Lißner *et al*, 2020; Zhu *et al*, 2020), and DBS TV (Menon, 2001), up to high-technology implementation such as environmental monitoring (Natcher *et al*, 2020; Okafor *et al*, 2020; Sohrabi & Ghahremani, 2021; Wang *et al*, 2020; Zhang *et al*, 2021) through satellites (Arnas, 2021; Emelyanov & Drozdov, 2021; Lee *et al*, 2021; Lu *et al*, 2020; Song *et al*, 2020; Yan *et al*, 2020). Microwave dielectric ceramics may be classified into three categories in the microwave frequency range, which namely low loss ceramics with tangent

loss less than 50×10^{-4} , medium loss ceramics with tangent loss between 50×10^{-4} and 0.1, and high loss ceramics with tangent loss greater than 0.1 (Goulas *et al*, 2020; Mahfoz *et al*, 2020; Peng *et al*, 2020; Tan *et al*, 2020; Wang *et al*, 2020; Yang *et al*, 2020; Zhang *et al*, 2020; Zhao *et al*, 2019). Low loss microwave dielectric ceramics of composition $\text{Ba}_{6-3x}\text{R}_{8+2x}\text{Ti}_{18}\text{O}_{54}$ (Kagomiya *et al*, 2007; Ohsato, 2001; Ohsato, 2007; Ohsato & Imaeda, 2003; Okawa *et al*, 2002; Santha *et al*, 2006) where R = rare earth exhibit interesting microwave dielectric properties which have latent force to develop in a broad range of applications covering telecommunication systems (Ibrahimov *et al*, 2018; Khan *et al*, 2017; Kotenko *et al*, 2019; Li *et al*, 2020; Palomba *et al*, 2018; Shulha *et al*, 2017; Toda *et al*, 2014) such as mobile and smartphones (Chen *et al*, 2021; Fan *et al*, 2021; Hartmann *et al*, 2020; Horwood & Anglim, 2020), wireless local area network (LAN) modules (Garropo *et al*, 2020; Marlali & Gurbuz, 2017) and intelligent transport system (ITS) (Bugeja *et al*, 2020; Fouchal, 2020; Malygin *et al*, 2018; Mastalerz *et al*, 2020; Mfenjou *et al*, 2018; Richter *et al*, 2020). Microwave dielectric properties of this ceramic can be systematically adjusted by replacing the rare earth ions or by partial substitution while maintaining the original crystal structure. The crystal structure of $\text{Ba}_{6-3x}\text{R}_{8+2x}\text{Ti}_{18}\text{O}_{54}$ as tungsten bronze type solid solution formed by corner sharing of TiO_6 octahedral. Cations with large ionic radii are situated within the three dimensional framework of TiO_6 octahedral connected at all vertices. The atomic ratio of titanium to oxygen on this framework is similar to perovskite-type structure (Katsumata *et al*, 2019; Liu *et al*, 2020; Ma *et al*, 2019; Oishi *et al*, 2021; Paiva *et al*, 2020; Qu *et al*, 2021). Microwave dielectric ceramics in the tungsten bronze structure or structures closely related to it, obtain the basic formula of $\text{Ba}_{6-3x}\text{R}_{8+2x}\text{Ti}_{18}\text{O}_{54}$ has the perovskite blocks of 2×2 unit cells with rhombic (A1) sites and pentagonal (A2) sites (see Figure 1). On this solid solution, two large sites covering Ba ions and R ions are situated at A1 and A2. The largest cation site which is A2 in this solid solution has the shape of pentagonal, and always filled with Ba ions. The medium site in this system that has rhombic spacing is A1, mainly partially occupied by Nd ions and Ba ions. The smallest triangular spacing in C site was usually empty according to the compositional formula. The crystal structure of this system has a special relationship with perovskite structure. In the case of the same ionic radius of the two cations, the transformation from tungsten bronze structure (Cao *et al*, 2020; Jin *et al*, 2020; Li *et al*, 2017; Wu *et al*, 2020; Zhang & Zuo, 2019; Zuo *et al*, 2020) to perovskite structure which is only left A1 site because of combination of A2 site and triangular empty spacing. This solid solution obtains orthorhombic (Akbudak *et al*, 2019; Hershkovitz *et al*, 2020; Laabidi *et al*, 1990; Myslyvchenko *et al*, 2020; Nielsen *et al*, 2020; Siddique *et al*, 2021; Weißpflog *et al*, 2020) crystal structure with space group of $Pbnm62$ and point group of mmm. The lattice parameters a , b , c of this system are $12.13 \text{ \AA}$, $22.27 \text{ \AA}$, $7.64 \text{ \AA}$ respectively with angles α , β , γ equal to 90° . The theoretical density of this system is 5.91 g cm^{-3} . This solid solution has a super lattice (Adhikari *et al*, 2020; Liu *et al*, 2011; Liu *et al*, 2020; Liu *et al*, 2014; Patil *et al*, 2016; Sreeparvathy & Kanchana, 2017; Wang *et al*, 2020; Zhou, 2014) via the c -axis with a double lattice of perovskite as indicated in Figure 1. The super lattice can be contingent on the tilting of TiO_6 octahedral as revealed in Figure 1. The tilting effects contribute to the density of the system that is the fundamental lattice superimposed which is with one layer on top of another layer or on a superstructure framework. The tilting of octahedral could be resulted by the ionic radius of cations located in the perovskite block. In the family of tungsten bronze structure, all the members have the general formula of $\text{Ba}_{6-3x}\text{R}_{8+2x}\text{Ti}_{18}\text{O}_{54}$. In addition, the structural formula can be defined as $[\text{Ba}_4]\text{A}_2[\text{Ba}_{2-3x}\text{R}_{8+2x}]\text{A}_1\text{Ti}_{18}\text{O}_{54}$. Ba^{2+} ions preferentially fill the A1 sites but only quarter of them can be accommodated which is $x = 0$. On the other hand, concentration of Ba ions in the A1 sites could be dismissed with the condition $x = 0.667$. Microwave dielectric ceramics with tungsten bronze type system of $\text{Ba}_{6-3x}\text{R}_{8+2x}\text{Ti}_{18}\text{O}_{54}$ with R = rare earth have been investigated as promising materials for microwave applications because of their relative high quality factor (Alesini *et al*, 2021; Aly & Zaky, 2019; Chen *et al*,

2020; Genco *et al*, 2018; Papari *et al*, 2020; Silva *et al*, 2018; Suwardi *et al*, 2020; Wang *et al*, 2020) and dielectric permittivity in microwave frequency region that could be implemented in mobile telecommunication system. Varfolomeev (Varfolomeev *et al*, 1988) who is the first researcher started to discover this solid solution using rare earth element as Nd and Sm. Ohsato and Negas also extended the investigation on this system by replacing rare earth elements as Pr and La for better understanding on their microwave dielectric properties (Ohsato, 2007). Replacement of R with Nd ions in this solid solution is the most promising candidates for high quality factor microwave devices among the four solutions. The various applications of Barium Neodymium Titanate is shown in Figure 2. The change in the concentration of cations and sintering conditions will make the structural properties and electrical properties of this material lead to wide range of applications. In addition, the cation distribution in the Barium Neodymium Titanate might influence the shape, morphology, and dielectric properties. Microwave dielectric ceramics could be utilized in mobile wireless technologies. Development of mobile wireless technologies (Almesaeed & Jedidi, 2021; Schimpf *et al*, 2019) started from year 1970 for first generation (1G) until year 2020 for fifth generation (5G) (Kumar & Gupta, 2018) are shown in Figure 3. The evolution of wireless generation can be seen in every 10 years. 1G (Lyytinen & Fomin, 2002) application only contribute to analog communication such as voice calls. The transformation from analog communication to digital communication started from 2G (Potter & Cohen, 2010) until latest generation. In more details, 2G transfer speed clocking, 3G (Pagani & Fine, 2008) enables more applications like video calling and multimedia messages, 4G (Boudriga *et al*, 2008; Iftikhar *et al*, 2011) with fast transfer speed can access to intelligent system functions for example smart homes. In the development of 5G technology (Han, 2020) provides faster transfer speed and low communication latency. The wave frequency for 5G can be categorized to low band spectrum which is below 6 GHz and high band spectrum that is between 24 GHz and 100 GHz. The main purpose of the review is to focus on the synthesis, morphology, properties and characterization methods of Ba_{6-3x}Nd_{8+2x}Ti₁₈O₅₄ ceramic. While the subject of dielectric nanostructures is enormously wide and many research articles are published on dielectric materials, Ba_{6-3x}Nd_{8+2x}Ti₁₈O₅₄ ceramic in particular constitute a special niche of microwave dielectric industry because of excellent microwave dielectric properties and good thermal and frequency stability. In addition, this review critically discuss approaches and the choices of synthesis method for use of Ba_{6-3x}Nd_{8+2x}Ti₁₈O₅₄ ceramic in a given applications. In brief methods such as sol-gel method (Badge & Deshpande, 2019; Belkhadir *et al*, 2019; Liu *et al*, 2020; Tan *et al*, 2020; Tang *et al*, 2019; Tohidifar, 2020), co-precipitation method (Farhat *et al*, 2020; Chou *et al*, 2020; Kum-onsa *et al*, 2020; Liu *et al*, 2020; Oliveira *et al*, 2020; Shashidharagowda & Mathad, 2020; Țucureanu *et al*, 2020; Zhang *et al*, 2020), solid state reaction method (Chain *et al*, 2010; Ganguly *et al*, 2011; Hay, 1995; He & Xu, 2019; Sang *et al*, 2013; Tong *et al*, 2019; Wong *et al*, 2013; Wongmaneerung *et al*, 2011; Yao *et al*, 2019; Zhang *et al*, 2018), and magnetic stirring method (Sun *et al*, 2018; Yan *et al*, 2019; Ye *et al*, 2019; Zhang *et al*, 2020) for the synthesis of BNT ceramics are discussed.

2. SYNTHESIS METHODS TO PREPARE BA_{6-3x}ND_{8+2x}TI₁₈O₅₄

There are a lot of synthesis techniques are utilized to prepare BNT ceramics such as sol-gel method, co-precipitation method, solid state reaction method, and magnetic stirring method. The techniques to synthesize BNT ceramics are shown in Figure 4. In addition, by doping other elements or oxides into BNT ceramics, the dielectric properties and the structural properties of the material can be enhanced. There are many advantageous for implementing solid state reaction method to synthesize BNT ceramic. By utilizing this technique, chemicals are toxic and expensive organic solvents normally do not involved in the reaction. Normally, all materials for performing this method are easy to get and cost friendly. The condition to undergo this process is quite economic and only room temperature with atmospheric pressure are required. For this

reason, solid state reaction method has been used in many ceramic processing stage by material researchers. Kaur et al. (Kaur & Narang, 2012) investigated electronic properties of complex Barium Neodymium Titanate ceramic using solid state reaction method. The raw materials for fabricating BNT ceramic are barium carbonate BaCO_3 and titanium dioxide TiO_2 , and Neodymium (III) oxide Nd_2O_3 high purity powders. There is no other solvent or chemical to be used in this process. The raw powders were weighted according to appropriate molar proportions and mixed in agate mortar for 12 hours in order to get homogeneous mixtures. After that the dried mixture was performed pre-sintered at sintering temperature of 1100°C for sintering time at 2 hours. The grinding process have been carried out after the sintering in order to get more fine homogeneous powders. An organic binder of PVA was used for strengthening the granules before shaping it. After that the granulated powders were compacted into pellets under a pressure of 75 kN. Finally, the pellets were sintered in a linearly programmable furnace at the sintering temperature of 1300°C for holding time of 2 hours. Li et al. (Li et al, 2004) studied high permittivity neodymium-doped barium titanate sintered in pure nitrogen using solid state reaction method. The starting materials were BaTiO_3 , Nd_2O_3 , and $\text{Ba}(\text{COOH})_2$. Before the mixing process, BaTiO_3 was calcined at 1000°C temperature. The purpose for the calcination process was to remove water and impurities within the powder. Later, the calcinated BaTiO_3 was mixed with other raw materials. The deionized water was added into the mixing process to make it became wet ball milling. In addition, ZrO_2 balls with diameter of 3 mm were mixing with the wet solutions which do not have chemical reaction with the mixtures. The mixtures were then sintered at 950°C temperature for 2 hours with the purpose to promote the diffusion of the dopants. The dried mixtures were combined with binder for pressing into disk form. Finally, the disks were sintered in the sintering temperature of 1250°C for 2 hours holding time. Buchanan et al. (Buchanan et al, 2011) developed barium titanate ceramics doped with Nd ion for piezoelectric actuator application. The starting materials were used for BNT ceramics included high purity BaTiO_3 powders with average particle size $1.23\text{ }\mu\text{m}$ and $\text{Nd}(\text{NO}_3)_3 \cdot x\text{H}_2\text{O}$ nitrates. All the materials were mixed with a solvent mixture of 40 vol. % de-ionized water and 60 vol. % isopropanol. The wet mixtures were added with binders and performed ball milling for milling time of 12 hours. After drying process, a weight amount of 0.25g of the dried mixtures was pressed into pellet at 7 MPa. Finally, the pellets were sintered at 1300°C for one and half hours sintering time. Wu et al. (Wu & Chen, 1999) reported the synthesis of BNT microwave dielectric ceramics using solid state reaction method. The starting powders for BNT synthesis were barium carbonate BaCO_3 and titanium dioxide TiO_2 , and Neodymium oxide (III) Nd_2O_3 high purity powders. Firstly, all raw powders were weighted according to stoichiometric formula, and mixed together with distilled water in polyethylene jar. In addition, ZrO_2 balls were introduced into the wet solutions which do not have chemical reaction with the mixtures. The wet mixtures were performed ball milling process for the milling time of 24 hours. In order to obtain dry mixtures, the wet solutions were calcined at 1100°C for 3 hours drying time in the atmosphere condition. The dried powders were then added with binders and pressed into disk for under 98 MPa. Lastly, all pellets were performed sintering process with the conditions of 1250°C sintering temperature and 3 hours sintering time. (Ratheesh et al, 1998) prepared $\text{BaO} - \text{Nd}_2\text{O}_3 - \text{TiO}_2$ system using conventional solid state ceramic route. The starting powders for this method were BaCO_3 and TiO_2 , and Nd_2O_3 high purity powders. Initially, stoichiometric amount of all starting powders were weighted and mixed with distilled water. The milling process was taken around 1 hour and then the wet solutions were dried at sintering temperature of 1200°C for 4 hours sintering time. The calcined powders were ground for another 1 hour and the fine solutions were pressed into cylindrical disc at 120 MPa. Finally, all samples were sintered at 1350°C sintering temperature and 4 hours sintering time. (Kolar et al, 1981) synthesized $\text{BaO} - \text{Nd}_2\text{O}_3 - \text{TiO}_2$ system using solid state method. The starting powders were high purity of BaCO_3 and TiO_2 , and Nd_2O_3 powders. According to their research work, the raw powders were

weighted according to appropriate proportions and mixed with alcohol solutions. It can be assumed that under alcohol condition able to enhance mixing process such as became more homogeneously. After the mixing process, the wet mixtures were underwent drying process. Drying process actually with the purpose to remove the ethanol inside the wet solutions, then the dried mixtures were pressed into the pellets with applied force. PVA works as binder actually is optional for pellet forming process, and may lead to porous surface when it has been removed. Finally, all samples were sintered at 1300°C sintering temperature for prolonged periods with intermittent cooling, crushing, mixing, and pressing to ensure homogeneity and to attain equilibrium. (Narang & Kaur, 2009) studied neodymium substituted barium titanate ceramics using solid state reaction method. The starting powders were high purity of BaCO₃ and TiO₂, and Nd₂O₃ powders. Firstly, all raw chemicals were weighted and mixed according to appropriate ratios. Ball milling process was used for combining all compounds and performing chemical reaction for more homogeneous solutions. The mixtures were then underwent drying process at the sintering temperature of 1100°C for holding time at 2 hours. After that, the calcined powders were pressed into pellet and sintered at final sintering temperature of 1300°C for 2 hours sintering time in a linear programmable furnace. (Ohsato & Imaeda, 2003) fabricated BNT ceramic utilized solid state reaction method for microwave applications as resonator. The starting powders were high purity of BaCO₃ and TiO₂, and Nd₂O₃ powders. Firstly, all compounds were weighted and mixed according to appropriate ratios. The milling process was performed in ethanol media with several milling balls for the milling time of 24 hours. After that, the wet solutions were dried at 1000°C in the air atmosphere for 2 hours. The milling process have been repeated again together with drying process. The calcined powders were combined with organic binder in order to press into pellet form at the applied force of 98 MPa. Finally, the pellets were sintered at 1460°C of sintering temperature and 2 hours of sintering time. Sol-gel method have been used for many nano materials preparation. Nanoparticles can be obtained by using this chemical solution process. A sol is a colloidal or molecular suspension of solid particles of ions in a solvent and gel is a semi-rigid mass that forms when the solvent from the sol starts evaporating where the particles left behind start to join together in a continuous network. The resultant product which comes out is in the form of colloidal powder or films. The main advantage of this preparation method is able to control microstructure of final product. The resultant particles are uniform and small size. As the cost friendly of nanoparticles synthesis technique, sol-gel method also required low temperature processing environment. (Rejab *et al*, 2011) prepared neodymium doped barium titanate using sol gel method. There are two main components to be used in sol gel method included precursors and solvents. The raw materials for preparing precursors are barium acetate (Ba(C₂H₃O₂)₂), titanium (IV) isopropoxide (Ti(C₃H₇O)₄), and neodymium (III) acetate hydrate (Nd.C₆H₉O₆.H₂O). On the other hand, glacial acetic acid and acetylacetone were used as solvents. Firstly, all raw materials were measured according to desired compositions. (Ba(C₂H₃O₂)₂) and (Nd.C₆H₉O₆.H₂O) were then dissolved in glacial acetic acid separately. These two compounds were mixed together with continuous stirring. For obtaining a clear solution, heating process has been carried out at temperature of 60°C. Later, the solution was allowed to release the heat to room temperature with continuously stirring. When the solution was in room temperature, Ti(C₃H₇O)₄ has been slowly added into the mixtures. At the same time, milky solution was obtained. After that, deionized water and ethanol were added into the milky solution for completing the hydrolysis process. The water to titanium ratio was fixed at 115. The final mixtures was continuously stirred for 4 hours and then heated at 90°C for 5 minutes. Lastly, the formation of gel was dried at 100°C for 24 hours and calcined at 700°C for 1 hour. The calcinated powders were then pressed into cylindrical shape with a pressure of 350 MPa. Finally, the cylindrical samples were sintered at 1250°C sintering temperature for sintering time at 3 hours. Co-precipitation is one of the easiest and conventional method to synthesize nanomaterials. BNT ceramics synthesized by co-precipitation method are of

controlled size, highly pure and homogeneous structure. Co-precipitation method for synthesis of BNT nanoparticles is shown in Figure 5. Basically, the starting materials were used in this method are inorganic salts such as nitrate, chloride, sulphate and so on. These inorganic salts are dissolved in water or any other medium that can form a homogeneous solution. It is necessary to adjust the pH of the solution in the range of 7 to 9. After that, nanoparticle precipitates can be obtained when the solvent is evaporated. The main concerns for crystal growth and aggregation of particles are the concentration of salt, temperature, pH value and rate of pH. After precipitation, the solid mass is collected and washed. The residue was then heated with the temperature of boiling point of the medium. The dried resultant products are in the form of hydroxide. The hydroxides are then calcined to transform the hydroxide into crystalline oxides. (Murugaraj *et al*, 1986) synthesized neodymium-doped BaTiO_3 ceramics using co-precipitation method. According to their report, BaTiO_3 was prepared from the successive precipitation of the precursor oxalate, $\text{BaTiO}(\text{C}_2\text{O}_4)_2 \cdot 4\text{H}_2\text{O}$. BaTiO_3 and then doped with neodymium was prepared by co-precipitation in the precursor, and the resulting product was adjusted with TiO_2 . The samples were pressed into disc form and sintered in air atmosphere at 1377°C of sintering temperature and 6 hours for sintering time. Magnetic stirring method widely used in laboratories that consists of rotating magnet or a stationary electromagnet that creates a rotating magnetic field. This technique is used to make a stir bar, immerse in a liquid, quickly spin, or stirring or mixing a solution. Much of the current magnetic stirrers rotate the magnets by means of an electric motor. It can be considered as the simplest method to prepare mixtures. Magnetic stirrers are silent and provide the possibility of stirring closed systems without the need for isolation, as in the case with mechanical agitators. Stir bars have smaller size which is more easily to be cleaned and sterilized than other devices such as stirring rods. They are used to agitate a liquid mixture or solution. The glass do not has interaction with magnetic field significantly, the chemical reactions of materials can be performed in glass vials or beakers. (Lee *et al*, 2014) prepared BNT ceramics using magnetic stirring method. The raw materials used were high purity of BaCO_3 and TiO_2 , and Nd_2O_3 powders. Firstly, the raw materials were weighted and mixed according to desired compositional formula. All of the weighted raw powders were mixed together with ethanol in a glass beaker. A stirrer bar was placed into the liquid mixtures for stirring purpose. The milling process was carried out with speed of 900 rpm and conducting in room temperature for milling time of 24 hours. The ethanol was used as mixing agent due to its insolubility and low boiling point. The wet mixtures were then dried for 24 hours in order to get dry powders. The final dried mixtures were pressed into pellet form and sintered at 1300°C of sintering temperature and 3 hours for sintering time.

Figure 1: Projection of Tungsten Bronze type structure of $\text{Ba}_{6-3x}\text{Nd}_{8+2x}\text{Ti}_{18}\text{O}_{54}$ solid solutions in c-plane

Figure 2: Applications of Barium Neodymium Titanate

Figure 3: Evolutions of Mobile Wireless Technologies from 1G to 5G

Figure 4: Synthesis Techniques for preparing $\text{Ba}_{6-3x}\text{Nd}_{8+2x}\text{Ti}_{18}\text{O}_{54}$ Solid Solutions **Figure 5: Co-precipitation Method for BNT Ceramics Nanoparticles Synthesis****Table 1: Summary of BNT Ceramics Processing Conditions of Major Synthesis Techniques**

Synthesis Methods	Milling time (Hours)	Sintering Temperature (°C)	Sintering Time (Hours)	Reference
	12	1300	2	(Kaur & Narang, 2012)
	-	1250	2	(Li <i>et al</i> , 2004)
	12	1300	1.5	(Buchanan <i>et al</i> , 2011)
Solid State Reaction	24	1250	3	(Wu & Chen, 1999)
	1	1350	4	(Ratheesh <i>et al</i> , 1998)
	-	1300	-	(Kolar <i>et al</i> , 1981)
	-	1300	2	(Narang & Kaur, 2009)
Sol-Gel	4	1250	3	(Rejab <i>et al</i> , 2011)
Co-precipitation	-	1377	6	(Murugaraj <i>et al</i> , 1986)
Magnetic Stirring	24	1300	3	(Lee <i>et al</i> , 2014)

4. APPLICATIONS OF BNT CERAMICS

Microwave dielectric materials have a wide range of applications from terrestrial and satellite communication including software radio, GPS, and DBS TV to environmental monitoring via satellites (Illahi *et al*, 2020; Jadav & Bhatnagar, 2020; Wu *et al*, 2011). In current technologies, it is necessary to develop a new designs of microwave dielectric materials or improved current microwave components to meet the desired specifications. For example, the demand of dielectric resonator (Firoozabadi *et al*, 2020; Mikhailovskaya *et al*, 2020; Roy & Basu, 2019; Singh *et al*, 2020; Wang *et al*, 2021; Zhang *et al*, 2020) still increasing in used in microwave telecommunication, satellite broadcasting and intelligent transport systems. The biggest challenge for materials scientists currently is the research and development in the field of device miniaturization (Masius *et al*, 2018; Song & Yan, 2020; Thiruramanathan *et al*, 2018; Yan *et al*, 2018) which is following the revolution in mobile phone and satellite communication systems. This also attributed to the increasing of cell phone users in current century. The materials development industry plays the important role to lead the revolutionary changes in wireless communication technology. BNT ceramics have revolutionized the microwave wireless communication industry by reducing the size and cost of filter (Ni *et al*, 2020; Pons-Abenza *et al*, 2020), oscillator (Jiao *et al*, 2014; Muenchausen *et al*, 2006; Tröls *et al*, 2015) and antenna components (Ambalgi & Sujata, 2019; Das *et al*, 2020; Ježová & Lambot, 2019; Xiang *et al*, 2020) in applications ranging from cellular phones to global positioning systems. The materials been used in

wireless communication technology have the specialized requirements and functions. The dramatic decrease in the size and weight of devices like cell phones and laptops were the implementation of miniaturization. Therefore, a continuing driving force for the discovery and development of increasingly sophisticated materials to obtain the same performance or improve the function with smaller size and weight is required. Dielectric resonator 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. BNT ceramics can be used as dielectric resonator as their high dielectric permittivity and low dissipation factor. The resonant frequency is measured by the overall physical dimensions and the dielectric permittivity of the materials and their immediate surroundings. BNT ceramics are the suitable candidate for dielectric resonator due to several key properties such as high quality factor, high relative permittivity, near zero temperature coefficient of resonant frequency. An optimal dielectric resonator that satisfies these properties simultaneously is difficult to achieve in a particular material. (Rejab *et al*, 2018) synthesized BNT ceramics and determined their resonant frequency in the frequency range between 50 MHz and 20 GHz using Network Analyzer. Based on their findings, the operational frequency of BNT ceramics was found to be tunable by doping different neodymium concentrations and BNT materials are suitable for use in X-band applications of dielectric resonator antenna. The current development of small dimension of microwave filter has motivated the research and practical interests of modern wireless communication system (Mondragón *et al*, 2020; Fernández *et al*, 2020; Shi *et al*, 2019; Tan *et al*, 2020; Zheng *et al*, 2020). Dielectric ceramics were used as two types of microwave filters such as band-pass filter and band-stop filter. In more details, band-pass filters are allowing transmitting desirable signals in the communication system. On the other hand, band-stop filters are suppressing undesired signals in the applications. BNT ceramics can be implemented in microwave transmission system with their good dielectric properties such as high quality factors and ease of excitation. Moreover, BNT ceramics can be used as replacement of traditional microstrip line filters because of low cost, commercial availability, and compact size. Nowadays, the fast trend of microwave communications systems required the miniaturized high quality oscillator. The main function of microwave oscillators (Dong *et al*, 2019; Kang *et al*, 2019; Sarkar *et al*, 2020) is to be a signal source of all microwave systems. BNT ceramics can be served as dielectric resonator oscillator with good output performance and dimension, and affordable cost compared to other alternative signal sources such as cavity oscillator or microstrip oscillator. BNT ceramics are the frequency-determining compounds that act as a microwave resonator thanks to the boundary established at the interface between the air and the high dielectric device. This boundary make it easy to couple RF power to this device and provides the resonance. Therefore, the properties of BNT ceramics included near zero temperature coefficient of resonant frequency, high dielectric constant and quality factor are fitted to the requirement of the applications of dielectric resonant oscillator. The electromagnetic spectrum utilized in satellite applications (Illahi *et al*, 2020; Mohammad Siddiky *et al*, 2020; Ramachandran *et al*, 2020; Sharma *et al*, 2020) such as super lenses, small electro-magnetic dipole antenna, microstrip patch antenna, invisibility cloaking, and biosensors required microwave dielectric materials to take part into them. BNT ceramic is the material that can be used in different types of polarized and monopole antennas with different working active resonance points located within the satellite bands, corresponding to WiMAX, Bluetooth, GPS or satellite communication and terahertz applications. As the personal communication system, handy portable cellular telephone that operate in 800 MHz band becoming common nowadays. The characteristics of portable telephone included small dimension for electronic components can operate at high

frequency region. BNT ceramics can replace stripline-type filter (Sekiya *et al*, 2011) due to their excellent performance in high frequency band. Moreover, higher quality factor and permittivity of BNT ceramics indicated the improvement of the performance which is degraded by miniaturization. Hyperspectral satellite images (Liu *et al*, 2020; Zheng *et al*, 2020) are widely been used from independent land mapping services to government and military activities. Therefore, wireless communications are required to transmit satellite images to the applications. The antennas play a significant role in the communication within the devices. In this point of view, BNT ceramics can be served as dielectric antenna that work in the frequency range of digital broadcasting. With small dimensional properties, multilayer ceramic capacitors (Cai *et al*, 2017; Kim *et al*, 2010; Li *et al*, 2018; Panda *et al*, 2020; Wang *et al*, 2020; Wang *et al*, 2012; Wang *et al*, 2020; Wang *et al*, 2017) are widely been utilized in electronic products. The miniaturization of electronics components required higher volumetric efficiency and the dielectric layer need to be micron or nano range. Therefore, reduction of insulation resistance increased the possibilities of dielectric breakdown. Dielectric breakdown is the one of the most common failure mechanisms in multilayer ceramic capacitors. In more details, the capacitor will start burning due to the leakage current applied. BNT ceramics obtained high dielectric constant at high frequency region which can absorb the leakage current to reduce the breakdown process.

5. OUTLOOK

The synthesis of microwave dielectric ceramics has increased recently. Thanks to fascinating properties of BNT ceramics among the dielectric ceramics such as high dielectric constant, high quality factor, and small temperature coefficient frequency, the material scientists are taking interest in the synthesis of this material. There are several synthesis techniques have been utilized for fabricating BNT ceramics and the performance of this material is processing dependent. Generally, BNT ceramics have a lot of applications including capacitors, mobile and satellite communication systems, antenna, oscillator, filter, sensor, and wireless communications. For widening the applications and properties of BNT ceramics, further studies are required. The dielectric properties of BNT ceramics can be enhanced by different concentration of neodymium for use in electronics applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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