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DEVELOPMENT OF HIGH-PERFORMANCE SINGLE- AND MULTIPHASE DIELECTRICS FOR ADVANCED MICROWAVE APPLICATIONS

Introduction. *The advancement of microwave technologies has necessitated the development of high-performance dielectric materials to enable miniaturization and enhance the functional characteristics of components such as radio frequency (RF) filters, dielectric resonators, and solid-state microwave sources.*

Problem Statement. *The design and fabrication of high-quality dielectric materials suitable for microwave applications across the decimeter, centimeter, and millimeter wave bands remains a critical challenge due to their essential role in next-generation radio-frequency and wireless communication systems.*

Purpose. *This study aims to develop advanced microwave dielectric materials based on single- and multiphase systems and to demonstrate their potential in improving the performance of wireless communication devices.*

Materials and Methods. *The crystallographic structure and dielectric properties of materials with various crystal lattices (e.g., perovskite, spinel) have been investigated through X-ray diffraction (XRD) and broadband dielectric spectroscopy. Prototype resonant elements fabricated from the synthesized microwave ceramics have been integrated and tested in wireless communication modules.*

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Results. *High-quality, thermally stable dielectric materials with tailored permittivity values suitable for decimeter- to millimeter-wave applications have been developed. These materials have been successfully used to fabricate dielectric resonators for RF filters and solid-state microwave generators. The incorporation of these resonators has provided lower phase noise and enhanced device performance compared to conventional quartz-based systems. These findings have demonstrated that dielectric resonators offer superior miniaturization and noise suppression, positioning them as critical components for low-noise, high-frequency devices in emerging 5G and 6G networks. Furthermore, the development of multiphase and high-entropy dielectrics, along with innovations in low- and ultra-low-temperature co-sintering techniques, has addressed the increasing demand for materials capable of supporting higher operational frequencies.*

Conclusions. *The high-Q dielectric materials and devices developed in this study meet international performance benchmarks and have the potential to significantly impact national technological priorities in telecommunications, defense, and security sectors.*

Keywords: high-quality microwave dielectric, crystal structure, single-phase material, multiphase material, dielectric resonator, solid-state generator.

Microwave (MW) dielectrics play a crucial role in modern society, enabling terrestrial and satellite communications that operate in the microwave region. Low-loss dielectrics are widely used in microwave systems as substrates for microstrip lines, coplanar waveguides in microwave integrated circuits, dielectric waveguides, resonant elements, and antennas [1—4]. These materials require a combination of high permittivity ε, minimal dielectric losses ($\text{tg}\,\delta \le 10^{-3}$—$10^{-4}$), or a high Q-factor ($Q = 1/\text{tg}\,\delta$, typically characterized by the product $Q \times f$ at a specific frequency), and high-temperature stability of electrical properties (temperature coefficient of resonant frequency $\tau_f \approx 10^{-6}\ \text{K}^{-1}$).

The choice of the permittivity of microwave materials is mainly determined by the frequency range of the communication system, the type of excitation wave, and the requirements for the optimal size of the dielectric elements. The value ε determines the size of radio components. The principle of miniaturization is based on the fact that the electromagnetic wavelength in a dielectric material decreases inversely to $\sqrt{\varepsilon}$. Therefore, high-Q thermally stable materials are essential for MW applications, with permittivity typically $\varepsilon \approx 60$ for decimeter range and lower, $\varepsilon \sim 10$—40 for centimeter and millimeter ranges.

In filtering and frequency-division multiplexing devices, high-Q dielectric resonators allow the preparation of ultra-narrowband filters (bandwidth ≈ 0.01% or 1 MHz) with very low losses (<1 dB). This has the dual benefit of significantly increasing the data transmission channels and enhancing the protection of the transmitted signals [3, 5].

Dielectric resonators (DRs) enhance security systems, road safety, medical devices, object detection, and power transfer through miniaturized filters and precise frequency control. In particular, dielectric resonators play a significant role in ensuring the ***safety of intelligent transportation systems***. Their compact size makes it possible to miniaturize microwave filters and antennas in secure communication units (SCUs) for vehicles. These SCUs enable secure data exchange between vehicles and roadside infrastructure. DRs have several advantages over traditional resonators. They effectively filter out the desired frequencies, which provides a better signal-to-noise ratio, making it more difficult to intercept or tamper with the data exchanged between vehicles. Their stability ensures reliable communication in various weather conditions. The timely transmission of important messages, such as accident warnings, road closures, and hazardous weather conditions, improves driver awareness and helps prevent accidents. In addition, secure communication between vehicles and traffic signals protects against hacking and allows for faster and more coordinated emergency response [6].

Microwave imaging, which uses the principle of permittivity, applies penetrating microwave radiation to detect objects hidden under clothing.

The system transmits signals that interact with different materials depending on their permittivity. Analysis of the received signals allows obtaining high-resolution images, accurately determining the location and nature (metallic or non-metallic) of hidden objects [7].

Antennas based on microwave resonators operating at 4.3—12.6 GHz hold promise for safe, ***early-stage cancer detection*** [8]. Their sensitivity to tissue dielectric properties allows tumor detection when they are still small and treatable, utilizing non-ionizing radiation for safety.

Dielectric resonators can be used for safe and efficient ***wireless power transmission*** (WPT) for medium ranges. Unlike far-field radiation methods (horn, patch, and metamaterial antennas, lasers, etc.), WPT with resonators relies on near-field coupling. This keeps energy concentrated around the resonators, minimizing exposure in the surrounding area, and making it suitable for environments with people or animals present. While effective for distances up to several meters, limitations include inherent energy loss even with high-*Q* resonators [9].

The future of secure communication in Intelligent Transportation Systems (ITS) likely involves a synergy of technologies. Cellular networks will likely remain the foundation, but millimeter-wave advancements may offer significant bandwidth increases and potentially even stronger security. While standards like WiMAX have limitations in range compared to cellular, their strengths in encryption and flexible architecture make them promising candidates for secure communication within specific ITS applications [6].

Dielectric resonators operating in fundamental vibrational modes have proven to be effective in the decimeter and centimeter wave ranges. However, their miniaturization for use in the millimeter wave range poses significant challenges. The fundamental modes at these high frequencies require too small a size of the DRs, making them impractical for applications. To overcome this limitation, research has focused on the use of whispering gallery modes (WGMs). WGM modes allow the use of larger DRs compared to their fundamental-mode counterparts (e.g., $H_{01\delta}$ mode). This not only simplifies the preparation but also allows for extremely high *Q*-factors, limited only by the material's inherent losses [5, 10—12].

Usually, high-*Q* MW dielectrics have been developed based on single-phase complex oxide systems with diverse crystal structures. This stemmed from the assumption that a single phase was essential for minimizing dielectric losses. The introduction of a secondary phase was believed to enhance electromagnetic energy scattering within the dielectric, consequently increasing losses. However, recent investigations [13—16] demonstrate the possibility of achieving higher *Q*-factors in multiphase systems compared to single-phase systems. Additionally, multiphase materials allow controlling the temperature dependence of electrical characteristics, a crucial aspect for practical applications of microwave dielectrics.

The aim of this work was the develop high-quality single- and multiphase microwave dielectric materials, and devices based on them for modern communication systems.

SINGLE-PHASE HIGH-Q MICROWAVE DIELECTRICS

Single-phase microwave dielectrics are developed based on thermostable compounds or solid solutions. Thermostable compounds, such as $BaTi_4O_9$ or $LaAlO_3$, exhibit inherent thermal stability of electrical properties. Solid solutions, like $Ba_{6-x}Ln_{8+2x/3}Ti_{18}O_{54}$ (Ln = La—Gd), (La,Al)TiO_3—$CaTiO_3$, or (Zr,Sn)TiO_4, achieve similar stability by manipulating the component ratio within their chemical composition. In particular, barium tetrathitanate, $BaTi_4O_9$ was the first reported single-phase, high-*Q* MW dielectric [17]. Later another thermostable material, $Ba_2Ti_9O_{20}$ was developed in Bell Laboratories [18]. A significant advancement came from Murata (Japan) with the development of (Zr,Sn)TiO_4-based ceramics [19]. These materials possess the ability to control the temperature coefficient of resonant frequency by adjusting the Zr/Sn ratio, a critical factor for practical applications. The permittivity (ε) of these materials typically ranges from 30 to 40.

Decimeter-wave applications require thermally stable microwave dielectrics with permittivity greater than 60, which is a crucial factor in achieving miniaturization in communication systems. Pioneering research [20, 21] has found high-*Q* MW materials with high ε in the BaO—Nd_2O_3—TiO_2 system in the TiO_2-rich region. These materials were identified as solid solutions of $Ba_{6-x}Ln_{8+2x/3}Ti_{18}O_{54}$ (Ln = La—Gd) crystallizing in a potassium-tungsten bronze structure ABO_3 [22]. This structure enables extensive isovalent and heterovalent cation substitutions, thereby facilitating control over the number of unfilled A-sublattice positions by influencing the partial redistribution of A-cations within five-, four-, and triangular channels. Such control over crystallographic structure allows for tailored electrophysical properties and preparation of materials with high permittivity (ε ≈ 70—80) and excellent thermal stability.

Ion-strain polarization from crystal lattice vibrations typically determines the permittivity of microwave dielectrics and its temperature dependence, which obeys the Curie-Weiss law. However, $Ba_{6-x}Ln_{8+2x/3}Ti_{18}O_{54}$ (Ln = La—Gd) materials exhibit deviations, with anomalies in their temperature dependencies, which arise not due to phase transitions [23]. These anomalies are attributed to lanthanide compression and the degree of electron localization [24, 25]. Cationic substitutions have facilitated the development of microwave dielectric materials with high permittivity, *Q*-factor, excellent temperature stability, and suitable for modern communication systems operating in the decimeter and centimeter wave ranges [26].

MULTIPHASE HIGH-Q MICROWAVE DIELECTRICS

Multiphase MW dielectrics can, in some cases, exhibit electrical characteristics comparable to those of single-phase ones. Furthermore, their synthesis can be achieved under milder conditions compared to single-phase MW dielectrics. Additionally, the reagents required for the fabrication of multiphase materials are often significantly cheaper.

Tantalates and niobates with perovskite structure

For several decades, dielectric resonators based on $Ba(Zn_{1/3}Nb_{2/3})O_3$ and $Ba(Zn_{1/3}Ta_{2/3})O_3$ have dominated microwave technology due to their high *Q* factor. The characteristics of such ceramics were first described in 1977 [27]. After this work, the researchers thoroughly investigated the materials of this system with a complex perovskite structure. Until recently, $Ba(Zn_{1/3}Ta_{2/3})O_3$ and $Ba(Mg_{1/3}Ta_{2/3})O_3$ were the most promising candidates for achieving $Q \times f$ values exceeding 100 000 GHz [28—30]. Dielectric resonators based on these materials exhibit low dielectric loss (high *Q*-factor) and minimal temperature-induced variations in resonant frequency (resonance frequency coefficient close to zero). These properties make them attractive for applications exceeding 10 GHz, particularly in communication satellite output multiplexers where they reduce dielectric losses and enhance microwave output power [31].

However, there are difficulties in the preparation of materials based on barium zincate-tantalate and barium manganate-tantalate. High sintering temperatures (1550—1600 °C) and extended durations (>20 hours) are required, followed by additional high-temperature annealing. This advanced treatment is required due to the complex B-sublattice structure, where various cations (e.g., Mg^{2+}, Zn^{2+}, Ta^{5+}) occupy octahedral sites. Achieving the optimal *Q*-factor requires the ordering of these cations in the B-sublattice, which is a slow process due to the limitations of diffusion mechanisms. Furthermore, the high content of tantalum oxide significantly increases the cost of such materials. The price of tantalum oxide increased by 500% between 2000 and 2001 due to the high demand for it in tantalum capacitors [32], and this trend is continuing. This price pressure requires the development of alternative dielectric materials where tantalum can be replaced by the much cheaper niobium. The choice of niobium is motivated by the close ionic radii and comparable chemical properties of these elements.

However, the replacement of tantalum ions with niobium in these perovskites leads to a decrease in the *Q*-factor. To solve this problem and improve the characteristics of niobium-containing materials, we investigated the effect of non-stoichiometry in the B-sublattice, where niobium coexists with zinc or magnesium ions [33]. This approach involved the synthesis of materials with deviations from the stoichiometric ratio, essentially introducing vacancies (unfilled positions) in the B-sublattice. These additional vacancies significantly accelerate the ordering of cations in the B-sublattice. Deviations from stoichiometry have a double effect on MW characteristics. On the one hand, minor deviations contribute to the ordering of cations under milder processing conditions, namely at lower sintering temperatures compared to tantalum analogs and without high-temperature annealing, which significantly increases the quality factor. On the other hand, excessive deviations lead to the formation of impurity phases that degrade the *Q*-factor. The optimal level of non-stoichiometry was determined to achieve a maximum of the *Q*-factor. This approach allowed us to obtain niobium-based perovskites with a permittivity of approximately 30, excellent thermal stability, and a high *Q*-factor ($Q \times f \geq 150\,000$ GHz). These multiphase materials show great promise for a variety of microwave applications, including solid-state generators.

Multiphase high-Q microwave dielectrics based on $BaTi_4O_9$

For the first time, a single-phase $BaTi_4O_9$ microwave dielectric was demonstrated by the authors [17]. This material had a permittivity of about 36—37, a quality factor of $Q \times f = 22\,000$—$25\,000$ GHz, and a positive temperature coefficient of the resonant frequency (τ_f) of about 15 ppm/°C. To improve the *Q*-factor and temperature stability of $BaTi_4O_9$, we investigated the effect of various oxides. Our results showed that the introduction of zinc oxide (ZnO) effectively improves the thermal stability. The interaction between $BaTi_4O_9$ and ZnO leads to the formation of an additional phase, $BaZn_2Ti_4O_{11}$ [34]. The increase in the concentration of ZnO does not lead to the formation of new phases but only changes the relative amounts of $BaTi_4O_9$ and $BaZn_2Ti_4O_{11}$ in the two-phase system. $BaZn_2Ti_4O_{11}$ has a negative τ_f, in contrast to the positive τ_f of $BaTi_4O_9$, and this contrasting behavior allows manipulating the overall thermal stability of electrical characteristics by adjusting the ZnO content. This feature is a significant advantage of multiphase microwave dielectrics over single-phase $BaTi_4O_9$. Moreover, the additional $BaZn_2Ti_4O_{11}$ phase has a significantly higher *Q*-factor compared to $BaTi_4O_9$. Consequently, the *Q*-factor of the two-phase $BaTi_4O_9$—$BaZn_2Ti_4O_{11}$ system achieves 65 000—70 000 GHz. These findings pave the way for the development of multiphase microwave dielectrics based on $BaTi_4O_9$—$BaZn_2Ti_4O_{11}$ system for various applications, including microwave radio filters and dielectric substrates in hybrid integrated circuits.

Microwave dielectrics combining phases with spinel and perovskite structure

The MgO—TiO_2 system contains several compounds, namely $MgTiO_3$, Mg_2TiO_4, and $MgTi_2O_5$. Among them, $MgTiO_3$ and Mg_2TiO_4 have promising characteristics for microwave applications (permittivity $\varepsilon \approx 14$—16, negative temperature coefficient of resonant frequency $\tau_f \approx -40 \div -50$ ppm/°C, and high *Q*-factors exceeding 150 000 at 10 GHz) [35, 36], however, their electrical properties are impaired by poor thermal stability. For practical applications, materials with close to zero τ_f values are required. To ensure thermal stability, the phase with a positive τ_f should be introduced in $MgTiO_3$ and Mg_2TiO_4, which have a negative τ_f. Such an additional phase shall be chemically inert with the magnesium titanates. Paraelectrics with a perovskite structure, such as $CaTiO_3$ and $SrTiO_3$, are

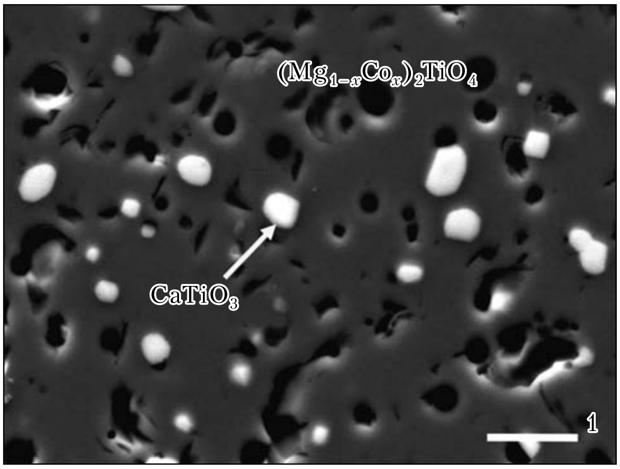

Fig. 1. Microstructure of ceramics $0.93[0.99Mg_2TiO_4 - 0.01Co_2TiO_4] - 0.07CaTiO_3$

well-suited for temperature compensation due to their high positive τ_f values [37, 38].

Our pioneering work [16] demonstrated that the addition of $CaTiO_3$ (or $SrTiO_3$) to $MgTiO_3$ and Mg_2TiO_4 allows the development of multiphase microwave dielectrics with volumetric thermal compensation. The multiphase material of Mg_2TiO_4–$CaTiO_3$ system, combining spinel and perovskite phases, exhibits high *Q*-factors, excellent thermal stability, and permittivity of approximately 20. The presence of multiple phases does not hinder a high *Q*-factor because the microwave wavelength (up to 30 GHz) is significantly larger than the ceramic's phase inhomogeneity, preventing additional scattering (Fig. 1). The promising properties of this material class suggest their potential for diverse microwave device applications in the centimeter and millimeter wave ranges. Furthermore, materials with high permittivity, excellent *Q*-factor, and temperature stability were prepared by using multiphase systems [39].

HIGH-QUALITY MICROWAVE ELEMENTS

The synthesized microwave dielectrics were utilized to develop diverse dielectric resonators for various frequency ranges. Coaxial DRs operating in the TEM mode were designed for the decimeter range, finding potential applications in radio filter manufacturing (Fig. 2, *a*). For the centimeter-wave range, "open" resonators and resonant blocks operating in the $H_{01\delta}$ mode, were created (Figs. 2, *b, c*). These DRs hold promise for radio filter and solid-state generator development. Additionally, dielectric substrates for hybrid integrated circuits and hemispherical dielectric resonators were developed (Fig. 3).

Dielectric resonators (DRs) offer a compelling solution for miniaturized and multifunctional microwave devices. They integrate with filters and semiconductors to achieve functionalities like frequency selectivity and stabilization, signal amplitude, and phase control within a single device. DRs can be used in antennas for both transmitting and receiving signals and for designing phase shifters and microwave generators. These technologies are essential for developing modern electronics operating in centimeter and millimeter wavebands.

Fig. 2. High-quality dielectric resonators: *a* — coaxial for the decimeter range; *b* — "open" for the centimeter frequency range at $H_{01\delta}$ type of oscillations; *c* — in the form of a hemisphere

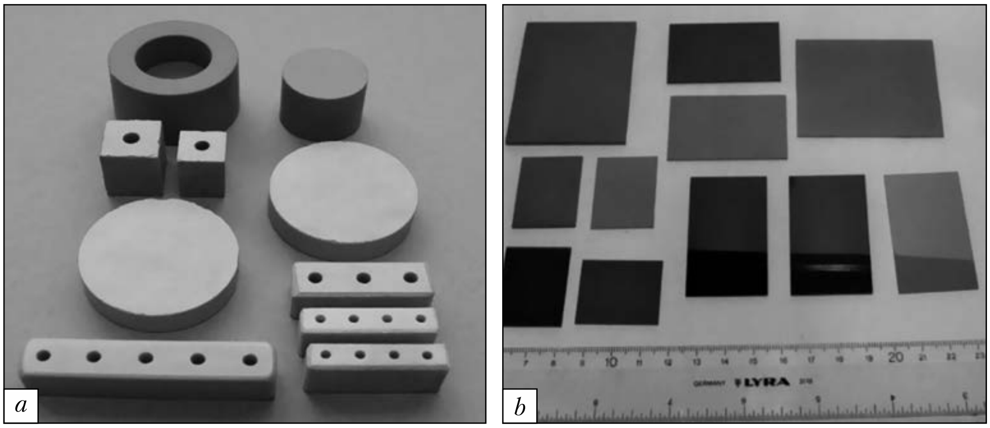

Fig. 3. Types of dielectric elements: *a* — monolithic ceramic blocks and "open" resonators of the centimeter frequency range for radio filters; *b* — dielectric substrates for hybrid integrated circuits

DRs are important for developing compact, frequency-stable microwave oscillators with high *Q*-factors and low noise levels. Traditionally, microwave frequency generation relied on quartz oscillators with frequency multipliers or phase-locked loop circuits. However, these designs have limitations such as insufficiently low phase noise and undesirable spectral components in the output signals. The high-*Q* DRs have enabled the creation of new microwave oscillators — compact, solid-state devices with best performance, located in free space or integrated into transmission lines. These oscillators achieve substantial size, weight, and complexity reduction while simultaneously improving reliability, stability, and miniaturization potential. Additionally, DR-based oscillators unlock a broader range of functionalities within a single device.

HIGH-Q MW DIELECTRICS IN SOLID-STATE MICROWAVE DEVICES

High-*Q* MW dielectrics are revolutionizing miniaturization efforts by enabling compact, lightweight, and multifunctional devices. Compared to traditional cavity resonators, DRs allow for much smaller solid-state oscillators and narrowband filters. This shift to high-quality components increases the performance of equipment to a level that surpasses traditional methods.

Conventional frequency synthesizers using traditional resonators still have high noise levels and spectral purity issues [40]. At the same time, modern microwave devices (radar systems, high-speed communication systems, and advanced measuring equipment) demand ultra-low phase noise in synthesized signals. In the mid-1980s, a phase noise level of −90 dBc/Hz for synthesized microwave signals was considered adequate. However, today's radar systems require significantly lower noise levels, typically around −100 dBc/Hz, and in some critical applications, even −110 to −120 dBc/Hz (at 1 kHz offset from the carrier frequency). Achieving such stringent noise levels is readily accomplished through high-*Q* DRs in master oscillator designs. Figure 4 shows the design of the oscillator with DRs based on tantalates with permittivity $\varepsilon = 24$ and a quality factor $Q \times f \approx 250\,000$. Low-noise bipolar transistors (BFP650E and BFP740F) were used as active elements. Ultra-low-noise microwave oscillators require the use of bipolar transistors with low noise in a specific frequency range. Field-effect transistors, on the other hand, are less suitable due to their inherent flicker noise, which can significantly increase the noise level near the carrier frequency by up to 30 dB.

Figure 5 (curve *1*) shows the phase noise of such an oscillator as measured by the E5052B signal source analyzer. Figs. 4 and 5 demonstrate that

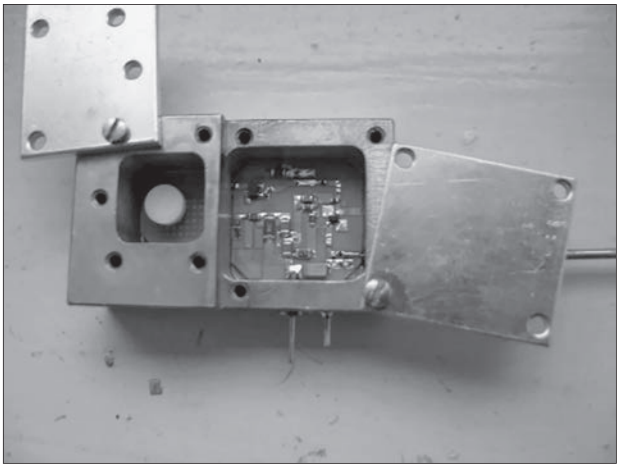

Fig. 4. Ultra-low-noise oscillator for a frequency of 10.355 GHz

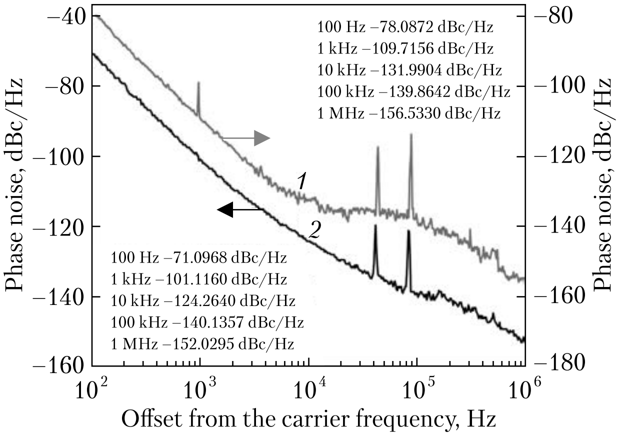

Fig. 5. Phase noise spectrum of ultra-low-noise oscillator based on complex tantalum oxide DRs at a frequency of 10.355 GHz (*1*) and titanium oxide DRs at a frequency of 10.501 GHz (*2*)

this relatively simple design achieves acceptable phase noise. At a frequency offset of 1 kHz from the 10.355 GHz carrier frequency, the noise level reaches approximately –110 dBc/Hz. Furthermore, the noise profile exhibits a significant drop, reaching –132 dBc/Hz at a 10 kHz offset and –140 dBc/Hz at a 100 kHz offset. Similarly, the use of DRs made of titanates with permittivity ε of about 36 and quality factor $Q \times f$ of about 100 000 in the same generator design leads to relatively low phase noise. Figure 5 (curve *2*) illustrates that phase noise depends on the *Q*-factor, especially in the vicinity of the carrier frequency. As can be seen, the noise level reaches –101 dBc/Hz at 1 kHz offset, –124 dBc/Hz at 10 kHz offset, and –140 dBc/Hz at 100 kHz offset, showing a trend comparable to tantalum-based resonators.

Quartz oscillators, even exhibiting exceptional phase noise performance, may not be the optimal choice for all reference oscillator applications. Frequency multiplication, a widely employed technique for achieving higher frequencies, introduces inherent noise from the multiplier circuit. This degrades the overall phase noise performance as expressed by the equation $\Delta G = 20\log(\mathrm{N})$, where N is the multiplication factor. For example, using a 100 MHz O-40-ULPN-100M as a reference oscillator to achieve an output frequency of 10 GHz ($N = 100$) increases the oscillator noise level from –160 dBc/Hz at 1 kHz offset and –180 dBc/Hz at 10 kHz offset to –120 dBc/Hz and –140 dBc/Hz, respectively, which approaches the performance of oscillator on dielectric resonator.

DR oscillators have clear advantages over the multiplication technique. Their compact size allows them to achieve comparable noise performance in a much smaller size. In addition, DR oscillators are generally more cost-effective. In particular, applications requiring wide bandwidth synthesis, such as modern radars, need to maintain spectral purity (low noise) over the entire range. In this case, DR oscillators can function as reference oscillators, with the desired lower frequencies obtained by the inverse frequency transformation, namely dividing the DR's high frequency [41].

Figure 6 shows designs of microwave synthesizers based on DRs oscillators as distinct functional blocks. The number of DRs employed can vary, as shown in the examples (three on the left, one on the right). This approach facilitates the individual fine-tuning and characterization of DRs before their integration into the complete synthesizer circuit.

For applications with fewer requirements and simpler product designs, the dielectric resonator can be directly integrated into the circuit, elimina-

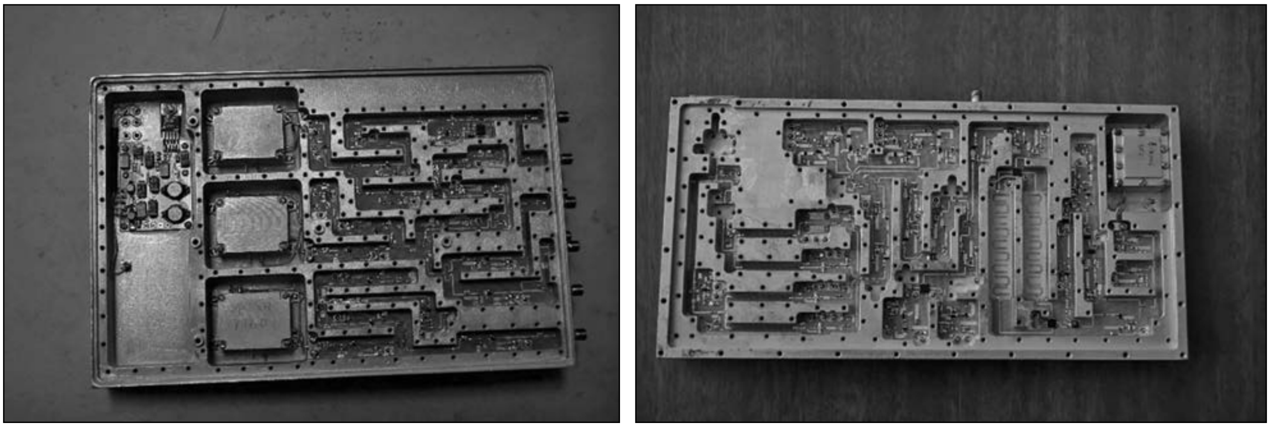

Fig. 6. Microwave synthesizer based on DR oscillators

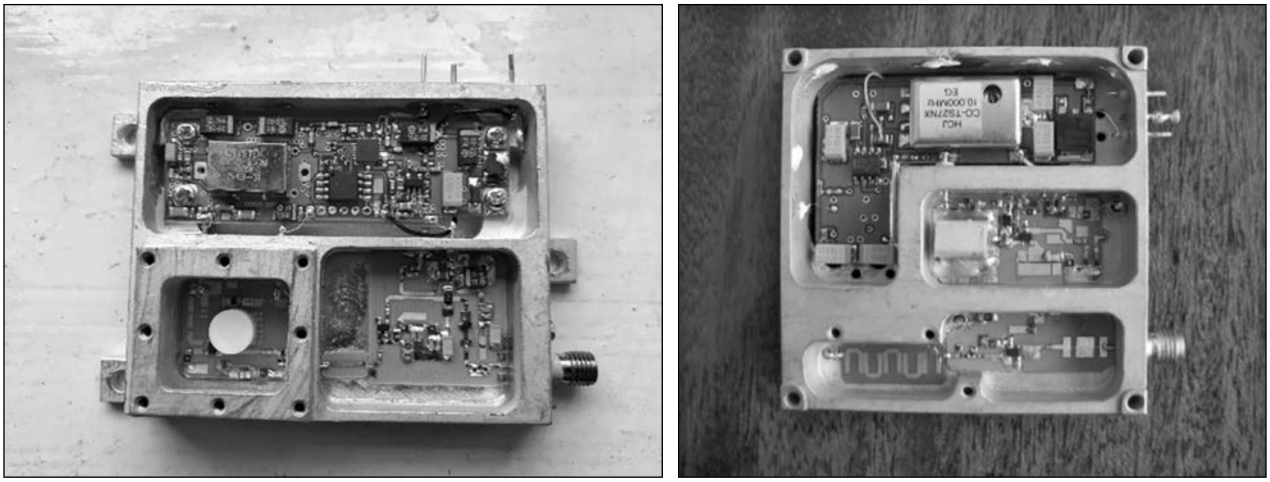

Fig. 7. Microwave heterodyne with increased frequency stability

Fig. 8. Designs of narrow-band microwave filters on the DRs

ting the need for separate modules. Fig. 7 demonstrates an example of this integrated approach.

Microwave synthesizers and receivers use narrow-band microwave filters that perform two important functions: clean the output spectrum of the synthesized frequencies and increase the sensitivity of the receiving devices. Although surface acoustic wave filters are good for this task, their operating range is typically up to 3 GHz [42]. For applications requiring higher frequencies, filters based on complex titanium oxide resonators are a good alternative. Figure 8 shows examples of such filters designed for center frequencies of 10.5 GHz and ~15 GHz, each with a bandwidth of several MHz.

EMERGING TRENDS IN MICROWAVE DIELECTRIC DEVELOPMENT

The transition to 5G communication requires a substantial expansion in the operational frequency bands used for wireless data transmission. This requirement stems from the exponential growth of mobile data traffic driven by factors such as the proliferation of Internet of Things (IoT) devices, advancements in virtual reality (VR), artificial intelligence (AI), and other bandwidth-intensive applications. To meet this surge in data demand, wider communication channels are essential, which can be achieved by utilizing higher frequency bands. These higher frequencies offer significant advantages, including increased bandwidth capacity, reduced latency, and the ability to support a greater number of simultaneously connected devices. However, higher frequency signals are characterized by shorter propagation ranges and a diminished ability to penetrate physical obstacles. This necessitates a denser deployment of base stations to maintain continuous network coverage [43, 44].

Higher frequencies in communication present challenges for traditional signal generation methods due to tighter tolerances and reduced spacing between radiating elements. Novel solutions are needed for efficient signal generation at these frequencies, such as optimized cylindrical dielectric resonators with dielectric plates for telecommunication applications and hemispherical dielectric resonators designed for ISM band, a group of radio frequencies internationally reserved for use in Industry, Science, and Medicine (Fig. 9) [43].

6G promises much higher bandwidths, lower latency, and greater device connectivity for advancements like the IoT. However, higher frequencies may lead to reduced coverage, higher costs, and signal penetration issues. 6G is still in early development, so final characteristics may differ from current projections [45].

The transition to 5G and 6G requires the development of new dielectric resonator (DR) materials with better performance. A high Q-factor ($Q \times f > 100\,000$ GHz) is paramount to minimize signal loss, which ensures DR efficiency [46]. In addition, simple and cost-effective manufacturing methods are crucial for reproducible properties and mechanically robust elements. To address these challenges, research efforts are focused on new materials for DR with improved performance.

The development of 5G and 6G technologies necessitates novel fabrication methods for microwave circuits due to limitations imposed by conventional high-temperature co-fired ceramics (HTCC). HTCC processing temperatures exceeding 1000 °C are incompatible with commonly used metal electrodes like silver (Ag) due to their lower melting points. Low-temperature and ultra-low-temperature co-sintering (LTCC/ULTCC) offers a solution that enables the formation of functional microwave circuits with integrated metal electrodes at significantly lower temperatures (700—1000 °C or <700 °C respectively) [45]. This approach reduces electrode degradation during the co-sintering process. Compared to LTCC, ultra-low temperature co-fired ceramics (ULTCC) is sintered at lower temperatures (400—700 °C) and has several advantages, including the ability to create flexible and lightweight electronics, integrating powerful devices on plastic-like materials, reducing energy consumption and environmental impact, and allowing for the manufacture of complex geometries and structures, expanding design possibilities [47].

High-entropy microwave dielectrics offer promising advancements for dielectric resonator development due to their unique and tunable properties not achievable in traditional materials [48]. These materials incorporate five or more elements in near-equal proportions, resulting in complex lattice structures compared to traditional dielectrics. This structural complexity significantly influences electrical properties. Investigations show that such dielectrics exhibit superior stability of electrical characteristics over time compared to traditional materials. By varying the composition, a wider range of permittivity values can be achieved, enabling optimization for specific frequencies. High-entropy microwave dielectrics often demonstrate lower dielectric losses than traditional materials and better resistance to changes in electrical characteristics over time.

High-entropy compositions attract research interest due to the possibility of optimizing the performance of the microwave resonator. Specific examples with promising characteristics include structures of spinel ($(Mg_{0.2}Co_{0.2}Ni_{0.2}Li_{0.4}Zn_{0.2})Al_2O_4$) [49], perovskite ($Sr_{0.9}La_{0.1}(Zr_{0.25}Sn_{0.25}Ti_{0.25}Hf_{0.25})O_3$) [50], and olivine ($Li(Gd_{0.2}Ho_{0.2}Er_{0.2}Yb_{0.2}Lu_{0.2})GeO_4$) [51]. The olivine-structured high-entropy ceramics doped with 3 wt.% H_3BO_3 exhibits a remarkably low sintering temperature (900 °C), minimal crystal lattice deformations due to its multicomponent nature, leading to a near-zero temperature frequency coefficient ($\tau_f \approx -7.4$ ppm/°C), and good overall microwave dielectric properties ($\varepsilon = 7.6$, $Q \times f = 11700$ GHz).

In the 30—300 GHz frequency range, multiphase ceramics based on $BaTi_4O_9$—ZnO, $MgTiO_3$, and Mg_2TiO_4 are attracting significant research interest (Fig. 10). Particularly promising for 5G applications are magnesium titanate ($MgTiO_3$) and magnesium orthotitanate (Mg_2TiO_4) due to their exceptional high Q factors ($Q \times f = 150\,000$—$160\,000$ GHz, measured using method of dielectric resonator [52] and a quasi-optical setup [53]), translating to low dielectric losses. Additionally, their cost-effective production makes them suitable for large-scale implementation.

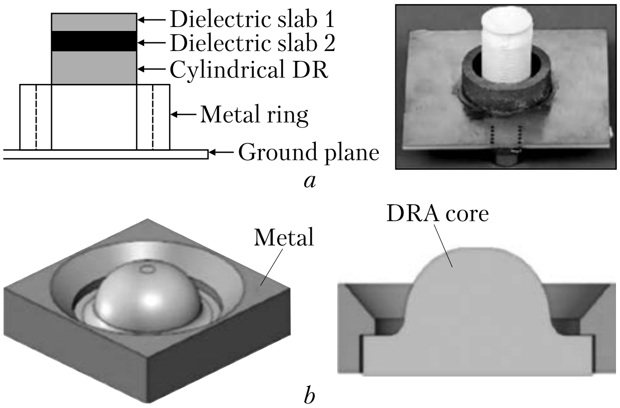

Fig. 9. Microwave dielectric resonators for phased array antennas: *a* — microwave dielectric resonators for phased array antennas: two dielectric plates and an outer metal ring at 10.7 GHz; *b* — hemispherical dielectric resonator (3D view and cross-section) at 24 GHz (*b*) [44]

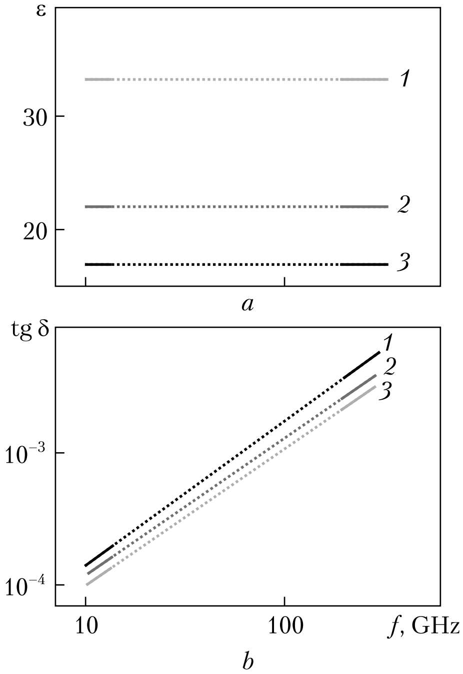

Fig. 10. Frequency dependencies of dielectric parameters of ceramic samples based on $BaTi_4O_9$—ZnO (*1*), $MgTiO_3$ (*2*), Mg_2TiO_4 (*3*) within frequency ranges of 8—14 GHz and 220—330 GHz and interpolation between these ranges (dotted line): *a* — permittivity ε; *b* — and dielectric loss tg δ

The studies of MW substrates for microwave applications in the range from 30 to 300 GHz have shown that ceramics are preferred over resins because of their lower dielectric loss, high thermal conductivity, and low coefficient of linear expansion, which ensures efficient heat dissipation and stable device operation [42]. Willemite-based ceramics materials stand out due to their near-zero temperature frequency coefficient (τ_f), making them the current gold standard for high-quality millimeter-wave communication devices. Japan has successfully implemented such MW devices in cutting-edge applications, including high-speed Wi-Fi (WiGig) operating at 60 GHz and vehicle radar systems functioning at 76 and 79 GHz [54].

Single-phase high-Q microwave dielectrics developed on thermostable compounds or solid solutions. These materials are characterized by three key parameters: permittivity (ε), quality factor (Q or $Q \times f$ product) and temperature coefficient of resonant frequency (τ_f). For decimeter-wavelength applications, permittivity around $\varepsilon \approx 60$ is desirable. Barium tetrathitanate ($BaTi_4O_9$) was first discovered as a high-quality single-phase microwave dielectric. More recent advancements include multicomponent materials like $Ba_{6-x}Ln_{8+2x/3}Ti_{18}O_{54}$ (Ln = La—Ga). These materials offer high permittivity ($\varepsilon \approx 70$—80) and thermal stability. The properties of such dielectrics can be fine-tuned through isovalent and heterovalent substitutions within their cationic sublattices.

Multiphase microwave dielectrics offer a compelling alternative to single-phase systems. They can be synthesized under milder conditions and exhibit several advantages, including high Q-factor, temperature stability, and the ability to tailor their properties by adjusting the ratio of constituent phases. Perovskite-structured tantalates and niobates, along with multiphase combinations of $BaTi_4O_9$, spinel, and perovskite phases, are prime examples of these materials.

The appearance of high-quality multiphase dielectrics provides an opportunity to develop advanced radio-electronic equipment operating in the centimeter and millimeter wave ranges. These advances can be realized in various microwave elements such as radio filters, solid-state generators, antennas, phase shifters, and transmission lines.

Modern microwave devices demand low-noise operation and narrowband filtering. While traditional quartz devices can achieve excellent quality, they fall short in noise level and spectral purity compared to dielectric resonator oscillators. Similarly, surface acoustic wave filters, while suitable for frequencies up to 3 GHz, become impractical at higher frequencies. This limitation necessitates the use of dielectric resonator filters for such applications. Consequently, microwave devices employing dielectric resonators emerge as a promising technology due to their superior performance, broader operational bandwidth, and advantages in miniaturization and cost-effectiveness.

The development of microwave dielectrics is experiencing a surge driven by the transition to 5G and 6G communication. These next-generation systems operate at significantly higher frequencies compared to their predecessors, demanding new material properties and production methods for dielectric resonators and antennas. Current research explores high-entropy microwave dielectrics, low-temperature co-fired ceramics (LTCC), and ultra-low-temperature co-fired ceramics (ULTCC) technologies. These techniques enable the fabrication of microwave elements at lower temperatures, promoting compatibility with polymer substrates and reducing energy consumption.

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РОЗРОБКА ВИСОКОДОБРОТНИХ ОДНО- ТА БАГАТОФАЗНИХ ДІЕЛЕКТРИКІВ ДЛЯ НОВИХ МІКРОХВИЛЬОВИХ ПРИСТРОЇВ

Вступ. Мікрохвильові пристрої потребують високодобротних діелектриків для досягнення мініатюризації та покращення технічних характеристик різних пристроїв, зокрема радіофільтрів, твердотільних генераторів тощо.

Проблематика. Розробка високодобротних діелектриків мікрохвильового діапазону в дециметровому, сантиметровому та міліметровому діапазонах є актуальною проблемою через їхню критичну роль у сучасних радіоелектронних системах.

Мета. Розробити високодобротні мікрохвильові діелектрики на основі одно- та багатофазних систем і охарактеризувати їхній потенціал для вдосконалення пристроїв бездротового зв'язку.

Матеріали й методи. Застосовано методи рентгеноструктурного аналізу та діелектричної спектроскопії для дослідження особливостей кристалічної структури та електрофізичних властивостей високодобротних матеріалів з різною кристалічною структурою (перовськіту, шпінелі тощо). Резонансні елементи на основі мікрохвильової кераміки випробували у пристроях бездротового зв'язку.

Результати. Розроблено високодобротні термостабільні мікрохвильові діелектрики з діапазоном значень діелектричної проникності для дециметрових, сантиметрових та міліметрових хвиль, з яких виготовлено діелектричні резонатори для радіофільтрів і твердотільних генераторів. Застосування останніх забезпечує низький рівень шуму та покращену продуктивність порівняно з традиційними технологіями. Діелектричні резонатори суттєво ефективніші за кварцові генератори для зменшення шуму та значно мініатюрніші, що робить їх пріоритетнішими для малошумних мікрохвильових пристроїв у сучасних системах зв'язку. Показано, що розробку нових матеріалів (багатофазні та високоентропійні діелектрики) та методів отримання (низькотемпературне та наднизькотемпературне спікання) зумовлено потребою застосування більш високих частот у 5G і 6G зв'язку.

Висновки. Розроблені високодобротні НВЧ-діелектрики і прилади на їх основі не поступаються світовим аналогам та є важливим вкладом у сектор національної економіки, безпеки й оборони.

Ключові слова: високодобротний НВЧ-діелектрик, кристалічна структура, однофазний матеріал, багатофазний матеріал, діелектричний резонатор, твердотільний генератор.