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Electric Field Distribution Optimization: Strategically Trapping To Enhance Component Rigidity

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Abstract: This scientific review investigates electric field distribution within ceramics and its role in mitigating edge effects and air ionization in applications involving Radio Frequency (RF) and High Voltage (HV). The exploration encompasses a thorough examination of the limitations associated with both organic and inorganic dielectrics. Additionally, the review delves into the potential of MgTiCa as a viable solution to overcome these challenges. Using a comprehensive analysis of electric field patterns and dielectric properties, this paper offers valuable insights to researchers and engineers working on electrical materials and components. We explore the complexities of electric field distribution in ceramics, revealing how edge effects and air ionization can be avoided, as well as the benefits of adopting MgTiCa for passive components in RF and HV applications as a dielectric**.**

***Index Terms* -** Electric field distribution; Ceramics; Edge effects; Air ionization; Dielectric materials; Radio Frequency (RF); High Voltage (HV).

I. INTRODUCTION

Dielectric materials form a critical component in the realm of passive components, particularly in applications involving Radio Frequency (RF) and High Voltage (HV). Organic dielectrics, such as polymers and resins, present advantageous qualities like flexibility and tunability. However, their application is tempered by potential shortcomings in thermal stability and high voltage performance when compared to their inorganic counterparts, notably ceramics. Among these ceramics, MgTiCa has garnered attention for its exceptional dielectric properties, including a high dielectric constant, low dielectric loss, and stability at elevated temperatures. These attributes position MgTiCa as a promising candidate for scenarios demanding both high permittivity and minimal loss, as often encountered in RF and HV systems.

The use of ceramics as dielectric materials for passive components in RF and HV applications holds particular interest due to its potential to reduce edge effects and air ionization. Understanding the limitations inherent in both organic and inorganic dielectrics is crucial when contemplating suitable materials for these applications. Inorganic dielectrics, exemplified by ceramics, offer elevated thermal stability, rendering them apt for HV scenarios. Nonetheless, challenges persist, particularly in terms of dielectric loss and limited tunability. Conversely, organic dielectrics provide the advantages of flexibility and tunability but may fall short in delivering equivalent thermal stability and HV performance.

This review offers a comprehensive survey of the current state of research surrounding the use of MgTiCa as a dielectric material for passive components in RF and HV applications. The discussion encompasses an exploration of its advantages and its potential to address the limitations inherent in both organic and inorganic dielectrics. Furthermore, the review concludes with a forward-looking discussion of potential avenues for future research in this domain, underlining the promising role of MgTiCa as a dielectric material for passive components in RF and HV applications [1][2].

II. DIELECTRIC LANDSCAPE IN RF AND HV APPLICATIONS: MATERIAL AND DESIGN INTEGRATION

The development of the prototype entails a dual-focused exploration involving material selection for dielectrics and electrodes and the determination of design parameters such as shape and dimensions [3][4].

2.1 Electrode Selection

Non-magnetic metals are imperative for electrodes in RF and HV applications. Silver, chosen for its availability and ease of deposition, and CuNiZn alloys, known for their machinability and hardness, are selected as optimal electrode materials.

2.2 B. Dielectric Considerations

In the dielectric realm, preference is given to ceramic-based materials over organics, owing to their superior thermal stability, thermal resistance, and dielectric properties. Notably, the sensitivity of organic materials like PTFE to very high voltage underscores the importance of selecting dense ceramics to mitigate electrical discharge.

2.3 Evaluation of Ceramics

The choice of dense ceramics can minimize electrical discharge risk because inorganic materials are mechanically stronger. Various ceramics, differing in chemical composition and density, were under evaluation based on dielectric permittivity, frequency stability, Q factor, and dielectric strength. Each dielectric is then modeled with specific dimensions to achieve a maximum capacitance value of 30 pF, guided by the capacitance formula [5][6][7]:

$$C = \varepsilon_0 \varepsilon_r . \frac{A}{e} \qquad (3.1)$$

With C is the capacitance, ε_0 the vacuum permittivity, ε_r the relative permittivity of the dielectric, A the plate area and e the dielectric thickness for a planar capacitor.

2.4 D. Cylindrical Pellets and Measurement Results

Cylindrical pellets, created through pressing and sintering, provide tangible representations of the selected materials. As outlined in Table 1, measurement results detail the evaluated ceramics' electrical properties.

Table 1. Measurement of electrical properties of selected ceramics

Properties / **Materials**	**ε_r @10MHz**	**Density (g/ cm^3)**	**Q factor**	**Breakdown voltage Impulse regime(kV)**	**tan(δ)**	**ε'**	**ε''**
BaZnTa	30	7.6	185	1	4%	25	1
TiZrNbZn	45	4.9	345	1.4	1.1%	127.27	1.4
BaMgTa	24	7.5	209	1.1	0.9%	122.22	1.1
BaSmTi	70	5.6	360	0.9	1%	90	0.9
ZrSnTi	35	5.3	350 @50MHz	1.3 @30MHz	2%	65	1.3
MgTi	15	3.10	389 @30MHz	1.3 @30MHz	1.3%	100	1.3

MgTiCa	16	3.15	401 @30MHz	1.4 @30MHz	0.01%	14000	1.4
Al2O3	10	3.95	420 @30MHz	1.4 @30MHz	0.1%	1400	1.4

$\tan(\delta)$: The loss tangent is defined as the ratio of the imaginary part of the permittivity ε'' to the real part of the permittivity ε' (with a negligible static conductivity):

$$tan\delta = \frac{\varepsilon"}{\varepsilon\prime} \qquad (3.2)$$

$$\varepsilon_r = \varepsilon' - j\varepsilon" \qquad (3.3)$$

Among the evaluated ceramics, MgTiCa, a High-Temperature Co-Fired Ceramic (HTCC), stands out with exceptional properties, including low capacitance variation, frequency stability, and high dielectric strength. As an NP0 ceramic, this material exhibits a low capacitance variation dC/C of only ±0.54% in the [−55; +125 °C] temperature range and frequency stability in the [1, 100 MHz] range [8][9]. It was tested in Galden fluids to estimate the breakdown voltage. It also has a high dielectric strength (40kV/mm measured value) at resonance frequency [10]. These attributes position MgTiCa as the chosen dielectric for the prototype design.

III. ELECTRIC FIELD DISTRIBUTION OPTIMIZATION FOR PROTOTYPE DESIGN

This section delves into the optimization of electric field distribution for the proposed prototype design, integrating insights from simulations and measurements. It encompasses the selection of electrode shapes, the addition of gaps, and the exploration of 2D design to enhance capacitor performance and mitigate the risks of edge effects, partial discharge, and air ionization. The detailed numerical simulations and experimental validations provide a comprehensive understanding of the proposed design's electrical characteristics.

3.1 Planar Prototype with Parallel-Plate Capacitors

A basic planar prototype with parallel-plate capacitors is introduced to observe electric field distribution. Two electrode shapes, square and circular, are considered, each tailored to meet the required specifications for 30 pF capacitance. The required properties for the analysis include electric conductivity, relative permeability, thermal expansion coefficient and these are selected from material property given in Table 2. Finally, an electric voltage of 40kV is applied across the electrodes. After applying boundary conditions, the results are shown in Fig. 1.

Table 2. Properties of selected metals

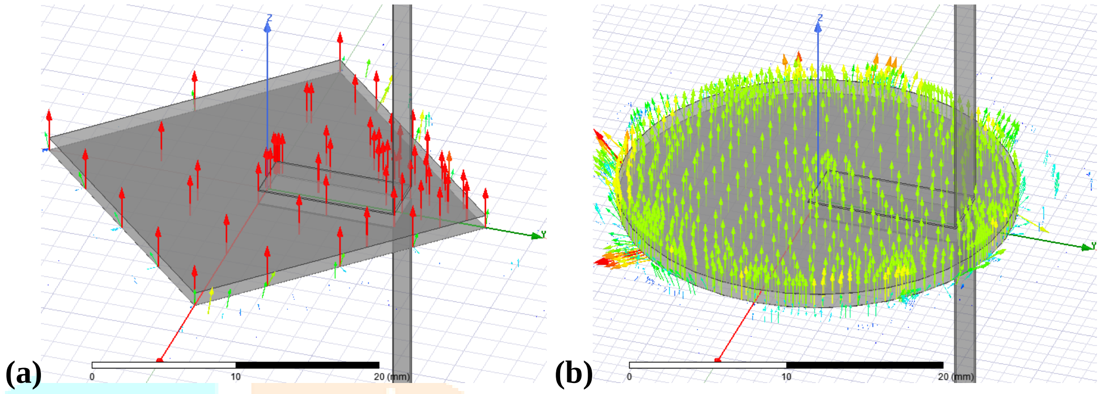
Metal / Properties	CuNiZn	Silver
Electric conductivity $(S.m^{-1})$	2.10^6	$61,3.10^7$
Relative permeability	0.99996	0.99998
Fusion temperature (°C)	1150	961,8
Young's modulus $(N.m^{-2})$	17.10^{10}	77.10^9

Analysis of the electric field distribution reveals that square-shaped electrodes accumulate electrical charges at corners, leading to edge effects and partial discharge. Circular electrodes, selected to mitigate these effects, demonstrate higher breakdown voltage and consistent electrical performance.

Then, the mesh element size and nodes are noted.

- Mesh element size of 10µm; mesh method tetrahedrons (to start from edge, face and then body).
- Mesh statics: 106837 nodes and 57195 elements.

In order to further limit electrical discharges and improve the voltage withstand, a gap is added around the electrodes. In this way the dielectric material is sized greater than electrodes in order to keep a margin around conductors as presented in Fig. 1. The divergent electric field lines (due to edge effect) will be confined in the ceramic material and no longer in the surrounding air, avoiding air ionization and then breakdown of the component [11] [12].



(a) **(b)**

Fig. 1. Electric Field Distribution in a Plane Capacitor with (a) Square-shape and (b) Circular-shape Electrodes

The electric field *E* inside the dielectric will be significantly reduced (inversely proportional to the dielectric relative permittivity) compared to electric field in air E_0. The electric fields E_0 (in air) and *E* (in the ceramic) are defined according the following expressions (in plane capacitor):

$$E_0 = \frac{\sigma}{\varepsilon_0} \qquad (3.4)$$

$$E = \frac{\sigma}{\varepsilon_0 \varepsilon_r} \qquad (3.5)$$

σ is the surface charge density, ε_0 the vacuum permittivity and ε_r the relative permittivity of the dielectric [13][14].

3.2 Added Gaps for Improved Performance

To further limit electrical discharges, gaps are introduced around electrodes, ensuring that the dielectric material surpasses the electrodes in size. This approach confines divergent electric field lines within the ceramic, preventing air ionization and breakdown of the component, as shown in Fig. 2.

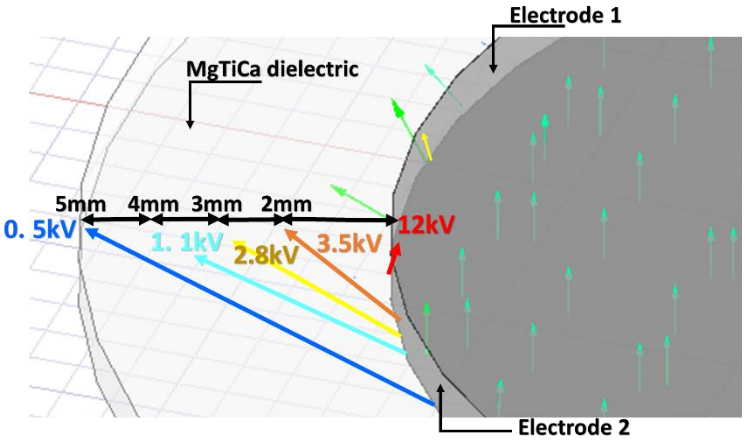
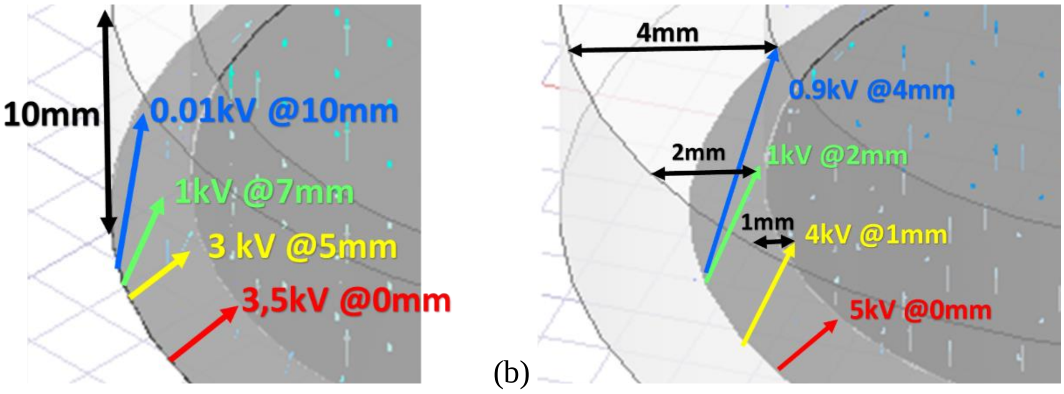


Fig. 2. Electric Field Distribution in a Circular Electrode Plane Capacitor with a Gap Around

A numerical simulation with a variety of gap widths shows a reduction in divergent gradient fields and a performance improvement. The addition of gaps significantly decreases the electric field voltage, enhancing the capacitor's capacitance value and self-resonance frequency.

3.3 Introduction of 2D Configurations

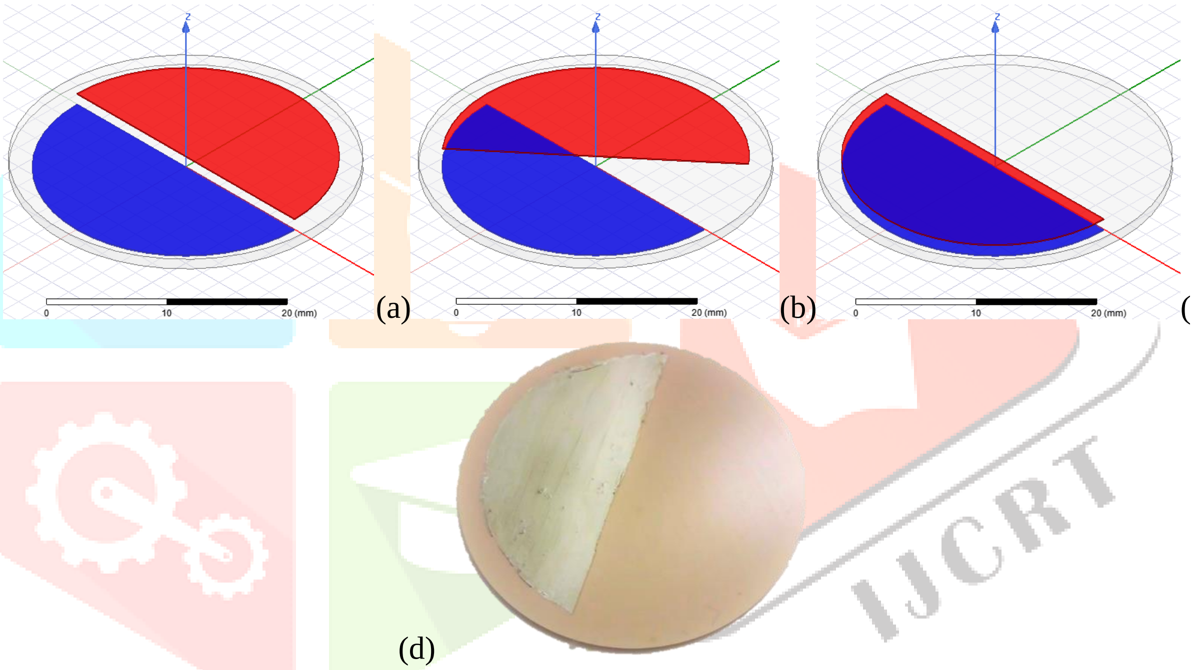
By using a 2D step around electrodes instead of a 1D gap, the gap width is reduced and the dielectric strength is increased. Numerical simulations with varying gap heights and widths reveal configurations that ensure uniform responses and meet RF requirements.



(a) (b)

Fig. 3. Electric field distribution with a 2D gap with (a) various heights and (b) widths for 7mm of height

To further improve capacitor performance, a shield is introduced around the electrodes. In addition to protecting against air ionization and edge effects, this 2D margin minimizes the gap width, increasing performance [15], as shown in Fig. 3.



(a) (b) (c)

(d)

Fig. 4. Plate location for (a) the maximum capacitance value, (b) an intermediate capacitance value and (c) the minimum capacitance value (d) the fabricated trimmer

Simulations are validated through the fabrication and testing of a prototype with a high-fired ceramic disk, as shown in Fig. 4 (d). In terms of capacitance, breakdown voltage, self-resonance frequency, and quality factor, the adjustable capacitor, with 2D margins and innovative shielding, exhibits excellent agreement between simulation and measurement results.

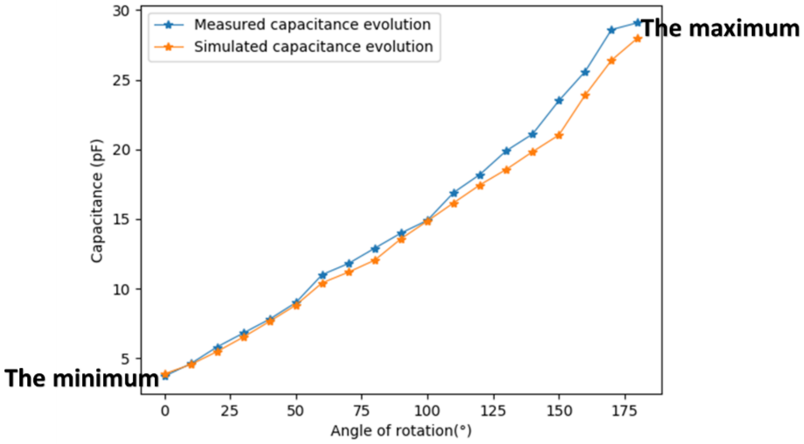


Fig. 5. Simulated and measured capacitance versus the angle of rotation at 10MHz

According to Fig. 5, the prototype demonstrates a capacitance range from 3.7pF to 30pF at 10MHz, with a fine-tuning capability of 1.6pF. Breakdown voltage, self-resonance frequency, and quality factor align closely with simulated values, showcasing promising results for the proposed prototype.

IV. CONCLUSIONS

In conclusion, this review explored the intricate dynamics of electric field distribution within ceramics, with a particular emphasis on addressing issues related to edge effects and air ionization in Radio Frequency (RF) and High Voltage (HV) applications. The limitations of both organic and inorganic dielectrics were thoroughly examined, laying the foundation for the investigation of MgTiCa as a promising solution. The dielectric landscape in RF and HV applications was scrutinized, emphasizing the critical role of materials and design integration in prototype development. Electrode selection, favoring non-magnetic metals like silver and CuNiZn alloys, was coupled with a meticulous evaluation of ceramic-based dielectrics. The review culminated in the identification of MgTiCa, a High-Temperature Co-Fired Ceramic (HTCC), as an exceptional candidate due to its remarkable dielectric properties.

The optimization of electric field distribution for the prototype design unfolded through detailed numerical simulations and experimental validations. A planar prototype with parallel-plate capacitors served as the foundation, with electrode shapes, mesh considerations, and gap additions carefully tailored to mitigate edge effects and partial discharge risks. The introduction of 2D configurations, incorporating shields around electrodes, further enhanced capacitor performance. By fabricating and testing a prototype, the proposed design demonstrated its capability to achieve capacitance ranging from 3.7pF to 30pF at 10MHz, demonstrating alignment between simulation and measurement results. Breakdown voltage, self-resonance frequency, and quality factor demonstrated impressive agreement with simulated values.

Aiming both to shed light on the complexities of electric field distribution in ceramics and to highlight MgTiCa's potential as a dielectric material in RF and HV applications, this review can be considered a valuable contribution. The insights provided herein offer a valuable resource for researchers and engineers navigating the intricacies of electrical materials and components in these critical domains. As technology advances, the outlined findings pave the way for future research endeavors, emphasizing the continual evolution of dielectric materials and their applications in RF and HV systems.

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