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Functional advances of microwave dielectrics for next generation

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Abstract

In coming age, new technologies for survivals of human beings on our earth are required. These technologies include for energy and natural resources conservation, waste disposal techniques, and reduction of global warming gases. To achieve this advanced functions of materials are essential. In this paper, new frontiers of microwave dielectrics are presented in relations with these energy issues.

The microwave dielectrics are familiar with radio frequency wave. The low loss dielectric materials are resonated by microwaves in air and change it to electric current in circuit, and vice versa. It is well known that the microwave materials have three important characteristic properties such as high quality factor Q, dielectric constant ε_r and temperature coefficient of resonant frequency TCf. These properties enable the following functions: (1) electromagnetic resonance, (2) electromagnetic-wave shortening, (3) electromagnetic-wave delay, (4) temperature variation of resonant frequency, (5) electromagnetic-wave absorption, and (6) other functions: such as transparency and refractive index. In this paper, for future excellent usages of these functions, some applications are presented showing the fundamental explanations. The content in this paper is planned for the publication in a handbook of advancements of functional ceramics.

Keywords: C. Dielectric properties; D. Silicate; E. Functional applications; Microwave dielectrics

1. Introduction

Microwave dielectrics are interesting materials which are friendly with electromagnetic waves. When it is irradiated with an electromagnetic wave, polarization is produced in these materials by alternative electric field of high frequency wave. The microwave dielectrics cause resonance which releases electromagnetic wave energy and vice versa. Fig. 1a shows an example of filter which consists of two column resonators made from microwave dielectrics between two electrodes. The introduction of an electric current through the left electrode, causes resonance in the column resonator at constant frequency and forms an electromagnetic field. Other column resonator causes resonance by the electromagnetic field, and output the electric current to a right electrode by the electromagnetic field. In the case of SAW filters (Fig. 1b) which have been replacing the role of dielectric resonator filters, must be fabricated by complex precise patterns such as comb-type electrode for resonance. On the contrary, the column dielectric resonator has simple structure.

In this paper, new and special functions based on the properties of the microwave dielectrics are presented as follows:

(1) Electromagnetic resonance
(2) Electromagnetic-wave shortening
(3) Electromagnetic-wave delay
(4) Temperature variation of resonant frequency
(5) Electromagnetic-wave absorption
(6) Other functions: transparency, refractive index

It is planned to publish these contents in the form of a hand book for advancements of function on ceramics. The papers in Refs. [1–7] are useful in understanding these functions of the ceramics.

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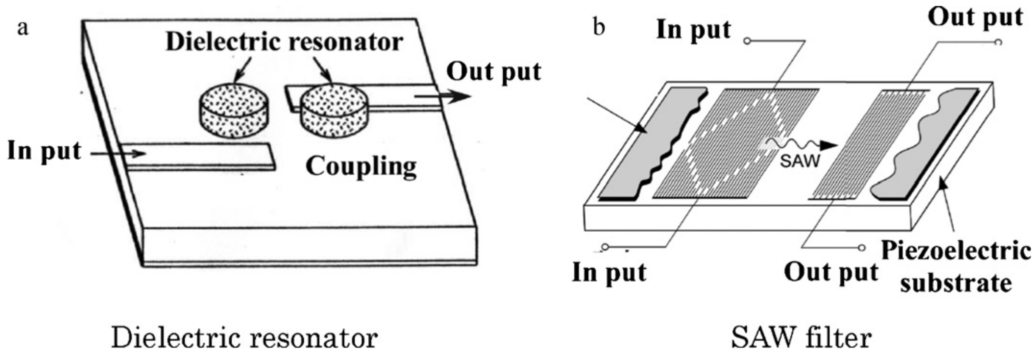

Fig. 1. (a) Dielectric resonator with resonate coupling. (b) SAW filter.

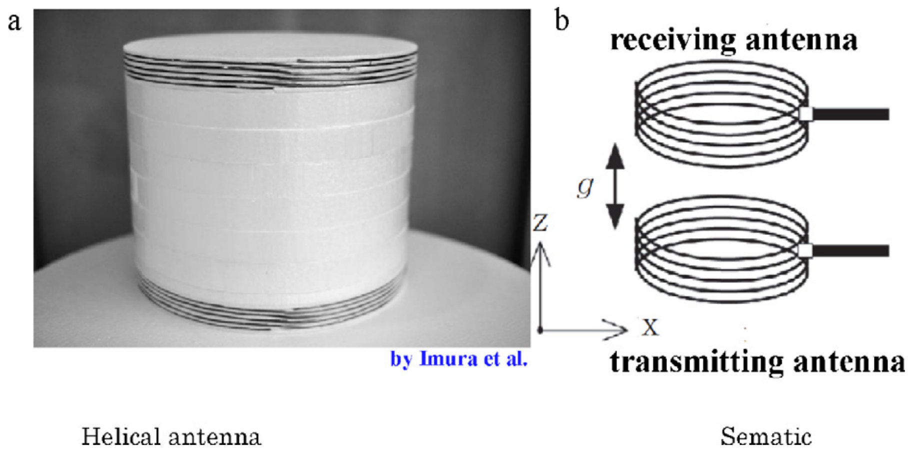

Fig. 2. Helical antenna with resonant coupling [9].

2. Three important microwave dielectric properties [1–4]

2.1. Quality factor Q

The most required properties of microwave dielectrics are quality factor: $Q = 1/\tan\delta$ which is related to how easily the dielectrics resonate when the materials are irradiated in an electromagnetic wave. Resonance is produced by alternative electric field of high frequency wave, by which the polarity is easily reversed with low energy loss such as in paraelectrics.

2.2. Dielectric constant ε_r

The ε_r has two important effects. One is reducing the wavelength λ in dielectrics according to following equation:

$$\lambda = \frac{\lambda_o}{\varepsilon_r^{1/2}}.$$

where, λ_o is wave length in vacuum. This effect is very important for reducing the size of mobile equipments. Another is time delay T_{PD} according to following equation:

$$T_{PD} = \frac{\varepsilon_r^{1/2}}{c},$$

where c is the velocity of light. As the ε_r decreases the time delay decreases and the signal transmission speed increases.

2.3. Temperature coefficient of the resonance frequency *TCf*

The *TCf* is expected to be near 0 ppm/°C for global usage with different temperature environments. The *TCf* has relationship with temperature coefficient of dielectric constant $TC\varepsilon$ as follows:

$$TC\,f = -\left(\alpha + \frac{TC\varepsilon}{2}\right).$$

where α is thermal expansion coefficient.

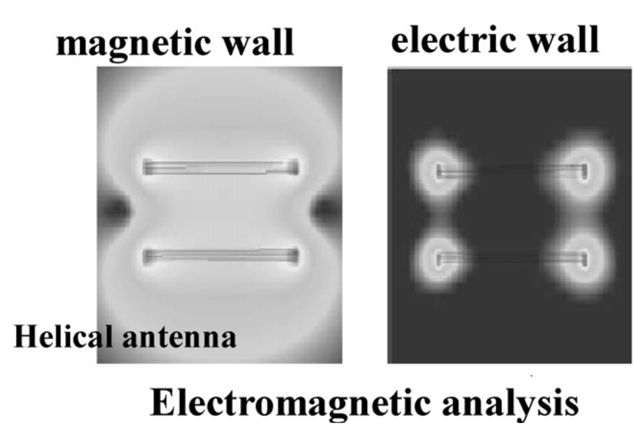

Fig. 3. Electromagnetic analysis of helical antenna with resonant coupling [9].

3. Details of advancement in the functions

The details and applications of six functions presented based on the three properties mentioned above will be shown for future trends.

3.1. Electromagnetic resonance

3.1.1. Microwave dielectric resonators

Microwave dielectrics are familiar with radio-wave as described in Section 1. There are many type resonators such as columnar resonator, strip-line resonator and LTCC resonator. The resonant modes such as $TE_{01\delta}$, TM_{010} and TEM are shown in some Ref. [1]. We can use these resonators for new applications.

3.1.2. Wireless power transfer

Recently resonant coupling used for filter in wireless communication system has been applied to wireless power transfer. Kurs et al. [8] applied self-resonant coils in a strongly coupled regime to non-radiative power transfer over the distance up to 8 times of the coil radius. They obtained a power of 60 W with ∼40% efficiency over the distance in excess of 2 m. Many other researchers reported the efficient wireless non-radiative mid-range energy transfer: the highest energy transfer is 800 W among the distance 5 m. The principle of energy transfer by electromagnetic resonant coupling can be represented based on the report of Imura and Hori [9]. Fig. 2 shows two helical antenna for the electromagnetic resonant coupling: one is transmitting antenna and another is receiving antenna: the diameter 300 mm, pitch 5 mm, 5 times scrolls, the distance 20 cm. Fig. 3 shows the resonant coupling simulation between two helical coils by electromagnetic field analysis (a) and the equivalent circuit schematic of the resonant coupling (b). Here, left figure is based on magnetic field coupling and right one is electric field coupling. In the case of helical antenna, the coupling is dependent on the magnetic field which is stronger than electric field coupling. This system with 17.5 MHz obtained 100 W with 95% efficiency of energy transfer.

The energy transfer distance by resonant coupling depends on the frequency. The transfer distance is as short as a few millimeters in the millimeterwave region, whereas in the microwave region long range transfer distance is used. The antenna becomes as large as a few tens of cm in the low frequency region. Here, microwave dielectrics can be considered as the antennas, because the size of antenna becomes small when the dielectric constant is large. We will present ceramics resonator with high dielectric constant for energy transfer antenna. The ceramic resonator is a kind of LC resonator which will be designed with non-refraction.

3.2. Electromagnetic-wave shortening

This function is still working for miniaturization of mobile communication devices. The resonant coupling antenna mentioned above will be miniaturized by using high dielectric constant materials.

3.3. Electromagnetic-wave delay

The silicates with low dielectric constant are useful for millimeterwave applications since silicates have short delay time T (ns/m) due to its low dielectric constants. Usually, though the delay time is a detrimental phenomenon, it could be used for useful applications. One of them is delay filter which adjust the delay time. On the other hand, multiple delay filters as shown in Fig. 4, which produce coherent electromagnetic waves with multiple different delay time, are useful for the measurement of the properties at short interval [10].

3.4. Temperature variation of resonant frequency

Microwave dielectrics have its origin from temperature stable capacitor with near zero $TCf/TC\varepsilon$. Fig. 5 shows several types of capacitors with different temperature properties. Moreover, a certain kind of capacitor can compensate the temperature coefficient of the system such as LC resonant circuit to 0 ppm/°C.

New applications can also be derived from the function of TCf for wireless temperature sensor using the relationship between temperature and resonant frequency. Though most of temperature sensor is connected by electric wire, this new dielectric sensor is wireless, so temperature on the special places such as aerospace and inside of atomic reactor could be measured.

Moreover, resonant coupling stated above could be applied for the wireless temperature sensor. Fig. 6 shows resonant coupling for temperature measurement of isolated place. The

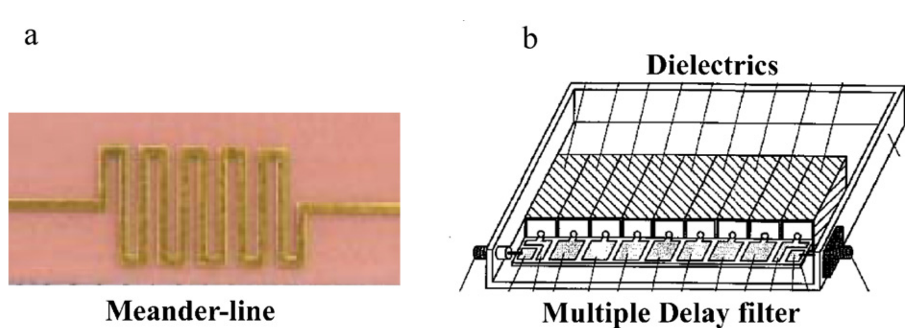

Fig. 4. (a) Meander-line on dielectric substrate, (b) multiple delay filter using dielectrics [10].

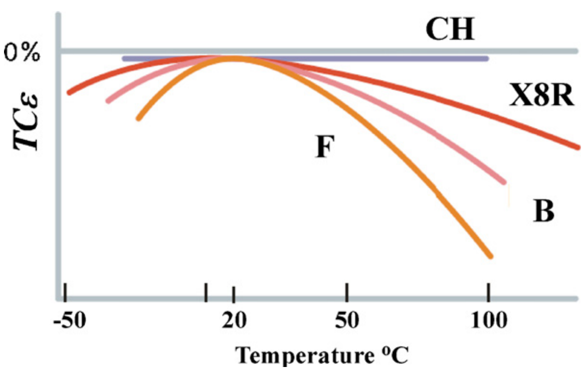

Fig. 5. Temperature properties for capacitors.

distance is a similar order of the wave length, and hence it depends on the wave frequency.

3.5. Electromagnetic-wave absorption

In the ubiquitous society exchanging information can take place anywhere anytime. The electromagnetic wave is filled in the life space of people, and causes a serious electric wave obstacle. The electromagnetic-wave absorber becomes essential at the same time to protect electronic equipment from the flood of the electromagnetic wave and to prevent the interference with other electromagnetic waves [11]. The principle of the electromagnetic-wave absorption is shown in Fig. 7 [12]. The absorber is constructed by an absorption layer and metal. The thickness of the absorber is $1/4\lambda$ of incident wave. The incident wave reflects on the absorber, and the reflection wave extinct based on the interference with reflected wave delayed by $1/4\lambda$ from the metal surface. Fig. 8 shows the non-reflective curve for absorber which is composed of the imaginary part vs. the real part of dielectric constant of absorber. Also the curve is plotted by the ratio of d/λ. Here, d is the thickness of absorber, and λ is the wave length.

Materials laid on the non-diffractive curve are right things for absorber. Both microwave materials with low loss and ferroelectrics with high loss are not suitable for the application as absorber.

Titanite $CaTiSiO_5$ having monoclinic *A*2/*a* with inversion symmetry ($\varepsilon_r = 22$, $\tan\delta = 0.09$) is one of microwave dielectrics, which is noticed for microwave ceramic absorber because of having an optimum loss [13]. Dielectric losses of Zn doped titanite increased and crossed the non-diffractive curve as

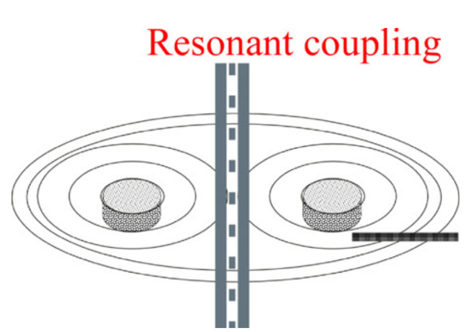

Fig. 6. Resonant coupling for temperature measurement of isolated place.

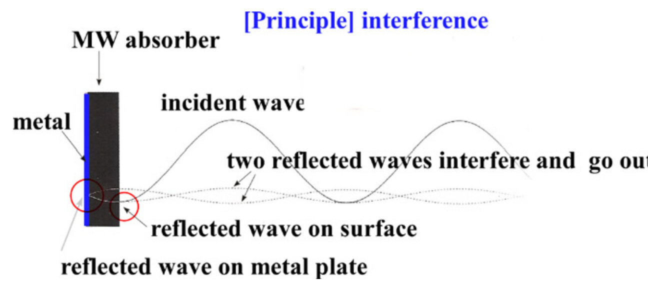

Fig. 7. Principle of electromagnetic-wave absorber [12].

shown in Fig. 8. The composition $CaTi_{0.95}Zn_{0.05}SiO_5$ has good properties, refractivity 32 dB at 57.5 GHz, for microwave absorber as shown in a figure imposed in Fig. 8. This ceramic material can be applied to relatively narrow-band absorber within 1 mm thickness for 10–70 GHz frequency region. Also Li doped $BaTiO_3$ with high dielectric constant can be applied for thin ceramic absorber [14]. Ceramic absorber is good due to its non-degradation by sunlight in the outdoors and is pollution-resistant, which give a comfortable-looking townscape.

3.6. Other functions: transparency and refractive index

As other functions, these are the refraction and the transmission for electromagnetic waves. Two applications on these functions are presented in the following section.

3.6.1. NRD-wave guide and dielectric lens antenna

Recently personal area network (PAN) using non condense high rate digital wireless telecommunications system has been demonstrated for millimeter-wave communication system. In the 1950s–1970s, big project for millimeter-wave communication system which was about to cover the world using low loss TE_{01} circular waveguide [15]. This project for the global communication system had been replaced by optical fiber communication system, because of difficulty of single mode transmission. After that, usage of millimeter-wave was adopted to wireless communication. Yoneyama et al., have been realizing a dream of millimeter-wave communication by the development of low loss NRD-wave guide based on knowledge obtained through the research of the global communication system [16,17].

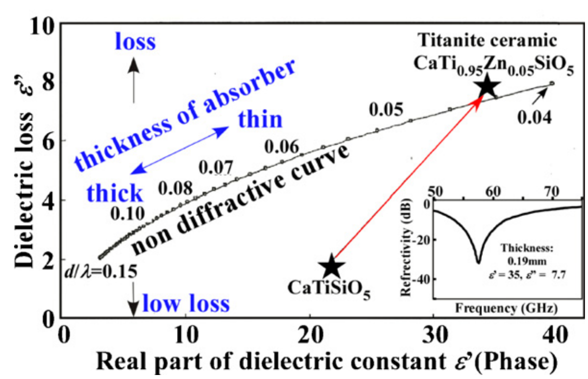

Fig. 8. Non diffractive curve for electromagnetic-wave absorber, and titanite ceramics $CaTiSiO_5$ is improved the absorption properties by doping Zn. A figure imposed is refractivity of Zn-doped titanite ceramic [13].

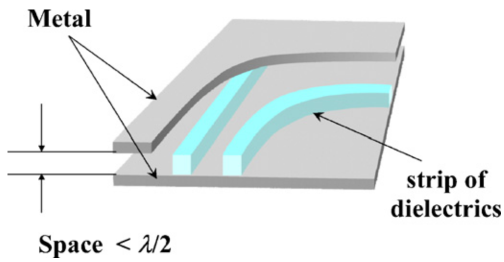

Fig. 9. NRD guide [17].

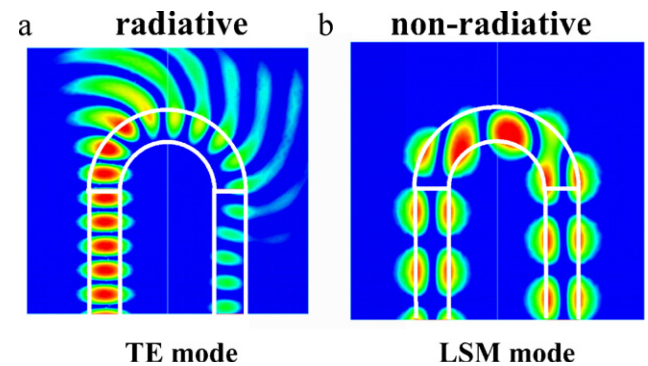

Fig. 11. Radiative on the bases of the mode on the bending of NRD-guide [17].

It is known for a long time that the dielectric wave guide for millimeter-wave has lower loss than micro-strip line. However, the wave guide was not realized because of electric emission from the curve and connecting parts of the wave guide. The NRD-wave guide has rightly solved these problems. It has low electromagnetic-wave emission structure in which the dielectric wave guide is located between two pieces of metal plates as shown in Fig. 9 [17]. However, its application has some difficulty because the transmission mode is a high order mode. Yoneyama [17] presented three kinds of magnetic modes and are shown in Fig. 10. It has a low loss longitudinal sectional magnetic mode (LSM-mode) on which the electric field is parallel to the conductor board. On the bending part of the NRD-wave guide, LSM single mode also shows non-radiative characteristics as shown in Fig. 11.

New materials for the NRD-wave guide are required instead of PTFE with low $\varepsilon_r = 2.0$, and low loss $Qf = 16{,}000$ GHz which is difficult for mass production by using the injection molding due to chemical stability [18]. The quartz glass fiber with ε_r 4, $Qf = 2{,}100{,}000$ GHz [19] used for optical fiber might be a candidate for the wave guide material. The availability of a new material will bring innovation on the millimeter-wave communication with high rate and high speed transmission: using the millimeter-wave fiber inside a city and the millimeter-wave wireless communication between the cities. Glass or ceramics fiber with low loss (high Q) should be expected for the new wave guide materials.

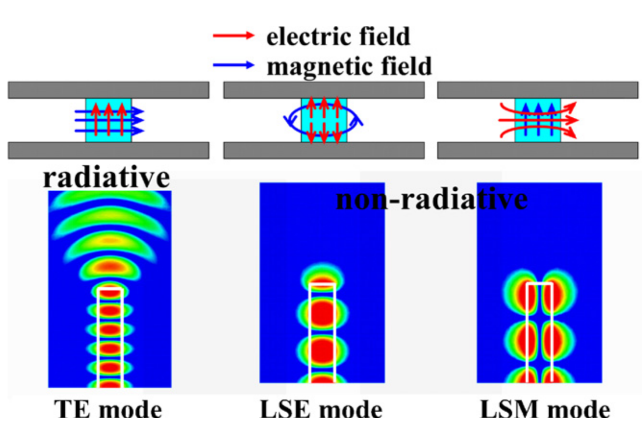

Fig. 10. Radiative on the base of the transmission modes [17].

3.6.2. Transparency ceramics

The microwave dielectrics are candidates for transparent ceramics, because of the high refractive index of the paraelectric materials without birefringence (double refractions). Paraelectric alumina Al_2O_3 is representative of transparent ceramics made first, and has been used as transparent ceramics [20]. However, as the alumina belongs to a trigonal system (R-3c, No. 167), the transmissivity is only 20–30%. The anisotropic materials have birefringence which cause scattering of light. Transparent ceramics ‘‘Lumicera’’ produce by Murata Manufacturing Co., Ltd. is microwave dielectrics with cubic system of paraelectric materials [21].

Lumicera is epoch-making materials with a high refractive index ($n_d = 2.08$) exceeding the optic glass which has high light transmissivity. The Lumicera was fabricated with good densification from microwave dielectric materials using high purity raw materials. This material is nothing but the complex perovskite compound BMT ($Ba(Mg_{1/3}Ta_{2/3})O_3$) which is the king of the microwave dielectrics. Lumicera has been fabricated by using the knowledge of microwave dielectrics. One of these knowhow is maintaining the cubic structure for better transmissivity, which changes to an ordered structure of trigonal system by long time sintering or annealing.

The Lumicera is compared with quartz optical glass as shown in Fig. 12a which shows the transmissivity as a function of wave length from the visible to the infrared light. Lumicera shows extremely high transmissivity from visible light (380–780 nm) to the middle infrared (−6000 nm). Contrarily quartz

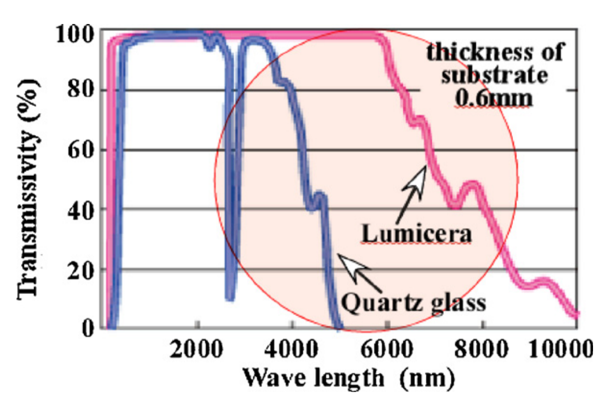

Fig. 12. Transmissivity of Lumicera compared with quartz glass. Transparent region expanded to middle IR region [21].

glass has absorption peak (ca. 2700 nm) by Si–O bond and suddenly decreased transmissivity at around 4000 nm. So, the Lumicera is expected for applications also for a middle infrared region.

Lumicera was applied to zoom lens for digital camera utilizing the function of light transmission and high refractive index. The conventional light transmission ceramics has insufficient light transmission rate [22]. Furthermore, the high refractive index made it possible to downsize a complicated zoom lens.

The transparent ceramics with high transmissivity are limited to the paraelectrics without birefringence. As most of the microwave dielectrics are paraelectrics, they are possibly good candidate for transparent ceramics. The transparent ceramics could be applied for new optical elements in middle IR frequency, and also for collaboration functions between electromagnetic-wave and light.

4. Conclusions

The microwave dielectric materials have revolutionized the wireless mobile communication system through the function of electromagnetic resonance and electromagnetic-wave shortening. In this paper, microwave dielectrics being familiar with electromagnetic-wave are represented for the applications in the new frontiers of utilizing the coupling between electromagnetic were and paraelectric materials. I wrote this paper with a strong belief because within this century new applications and devices appeared over the commonsense such as metamaterials, electro transmission by resonant coupling, and superconductor by cement material.

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