IEEE Access
Multidisciplinary ⁝ Rapid Review ⁝ Open Access Journal

Received November 18, 2019, accepted December 4, 2019, date of publication December 16, 2019,
date of current version December 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2959848

Evolution and Analysis of Dielectric Properties of Typical Materials Under Strong Microwave Field

YONG GAO[1], **EN LI**[1,2], **GAOFENG GUO**[1], **HU ZHENG**[1], **AND YANG ZHOU**[3]
[1]School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
[2]National Engineering Research Center of Electromagnetic Radiation Control Materials, Chengdu 611731, China
[3]College of communication Engineering, Chengdu University of Information Technology, Chengdu 610225, China

Corresponding authors: Yong Gao (gy_eee@163.com) and Yang Zhou (yangzhou@cuit.edu.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFF01013600 and Grant 2018YFF01013603, and in part by the National Natural Science Foundation of China under Grant 61671123 and Grant 61001027.

ABSTRACT The complex dielectric constant is the intrinsic parameter of microwave material, and the accurate acquisition of its value is critical for its application. Generally, the dielectric properties of microwave materials are obtained under weak electromagnetic field. However, with the continuous development of high power microwave technology, the microwave field intensity around materials gradually increases, and the test results of the dielectric properties of materials under the weak electromagnetic field will not be able to characterize the test results under the high power environment. Therefore, a novel testing technology based on the resonator method is proposed, which provides an effective solution for the measurement and characterization of microwave dielectric properties of materials under strong microwave field. Based on the constructed system, the evolution rules of the microwave characteristics of four typical materials are obtained. In the experiment, the temperature of the samples is precisely monitored, and the evolution rules of the temperature characteristics of the dielectric properties of the samples under strong and weak microwave fields are compared. The comparison results demonstrate that the dielectric properties of materials under strong fields are related not only to the microwave heating effect but also to the mechanism of the non-thermal microwave effect.

INDEX TERMS Dielectric property, measurement, microwave field, non-thermal microwave effect.

I. INTRODUCTION

The dielectric property of materials have a guiding role in the application of materials, especially in the microwave frequency band [1]. Generally, there are two main kinds of methods to acquire dielectric properties of materials: network parameter method and resonance method. The network parameter method is mainly to obtain the scattering parameters of the single port or double ports network, which contains the samples to be tested, and according to the relevant theoretical calculation formulas, the dielectric properties of the materials are obtained [2]–[4]. As for the resonance method, the samples are usually placed at the strongest electric field in the resonant system. Based on the changes of the parameters of the resonance system before and after putting the samples into the resonance system and the perturbation theory formula, the dielectric properties of the samples can be acquired [5]–[7]. Commonly, the former method is suitable for measuring materials with high loss, while the latter one is more appropriate for those materials with low loss. However, both the first and the second methods use low-power signals to measure the dielectric properties of the samples. That is to say, all the dielectric properties of materials are measured under the environment of weak microwave field.

Nowadays, after 50 years of development, high power microwave technology gradually matures. Undoubtedly, the miniaturization of circuits and systems is inevitable with the development of wireless communication [8]–[10], leading to the space power will be three or four orders of magnitude in the future, and the field intensity around the materials will increase dramatically [11]–[14]. Whether the dielectric properties of materials under high power microwave environment can still be characterized by the measurement results of the dielectric properties of materials under weak microwave field environment worthy further consideration. Many scholars have already carried out some research on this issue [15]–[25]. It was demonstrated in [15] that external microwave fields can affect the dielectric

The associate editor coordinating the review of this manuscript and approving it for publication was Giovanni Angiulli.

properties of polar solution. In the experiment, the temperature effects caused by microwave heating are excluded by the flowing fluid, and the results validate the existence of a non-thermal microwave effect [16]. M. Zielinski have investigated the effect of microwave field on organic matter removal efficiency in biofilm, experimental results show that microwave radiation can greatly improve the removal efficiency of organic matter in biofilm, and the temperature fluctuation caused by microwave radiation is pretty small [17]. In [18], the effect of external high electric field intensity on I-V characteristics of 6H-SiC (a semiconductor material) single crystal was investigated. Experimental results show that the resistivity of 6H-SiC presents different change rates under the impact of pulse field intensity of 0.5 ∼ 80 KV/cm, and the stronger the pulse field intensity, the faster the change rate. However, non-thermal microwave effect does not always exist, or its existence may require certain conditions [19], [20]. In effect, radiation may tend to induce changes in some materials while others may not be affected [21]–[23]. In addition, some papers, such as [24], said that the tensile strength of polyethylene increase in the radiation environment, while [25] obtained the opposite conclusion. Therefore, the influence mechanism of high power microwave on materials needs to be further studied. It is of great significance to investigate the dielectric properties of materials under high microwave power.

In order to address above problem, a measurement system based on a compressed rectangular resonator is established to investigate the evolution of microwave dielectric properties of materials under high power microwave field intensity. The cavity perturbation technique is used to obtain the microwave dielectric properties of materials under different electromagnetic field intensity. In this paper, four typical materials are tested, the dielectric evolution rules along with the microwave field intensity is acquired. By comparing the evolution rules of dielectric properties under high microwave field and the temperature characteristics of dielectric properties under weak microwave field, we initially confirm that the existence of non-thermal effect of high power microwave. In the experiment, the temperature of the sample was obtained by the infrared thermal imager with high sensitivity.

II. MEASUREMENT THEORY ANALYSIS

A. MICROWAVE FILED STRENGTH CALCULATION THEORY

When obtaining the dielectric constant of material through the resonant cavity perturbation method, it is generally used to obtain the reflection coefficient of the resonant cavity with a single port or the transmission parameters of the resonant cavity with two ports, and obtain the changes of the resonant parameters of the resonant cavity before and after loading the sample. Finally, the dielectric properties of the material are obtained by inversion. In this paper, based on the traditional resonant cavity with two ports, we introduce a third port to the cavity, which is used for the stimulus signal to be insert into the cavity separately. The original two ports of the cavity are used to acquire the transmission parameters of the cavity under different microwave field intensity, and the evolution of dielectric properties of the sample is obtained using the cavity perturbation method. With that said, the measurement of sample performance is independent of the construction of strong electromagnetic field environment, as is shown in Fig. 1. The stimulus signal to establish the strong electromagnetic field is put into the cavity through port 3 and the measurement signal is coupled into and out of the cavity by ports 1 and 2. In order to reduce the effects of stimulus signal on measurement signal, the two signals are chosen as two different resonant cavity modes, and two band-stop filters, with a stop frequency same with the frequency of the stimulus signal, is introduced to the measurement end, which can further suppress the influence of stimulus signal. By adjusting the output power of the original stimulus signal of VNA 1 or the gain of the power amplifier, the actual input energy into the cavity can be adjusted, which can change the microwave field intensity around the materials under test in the cavity.

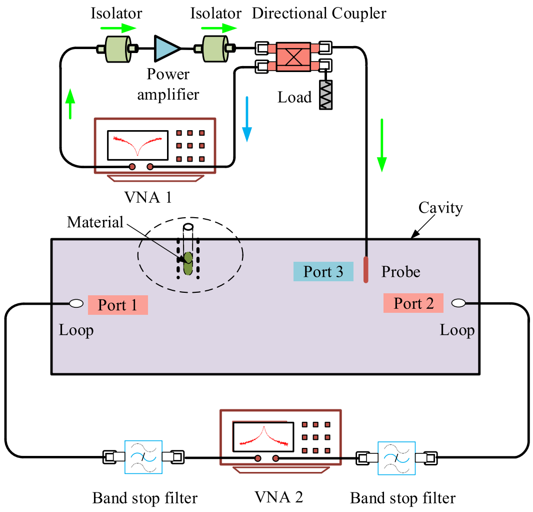

FIGURE 1. **Model of the measurement system.**

In Fig. 1, assuming that the output power signal provided by the vector network analyzer 1 (VNA 1) is P_s, then the stimulus signal power arrives the electrical probe is:

$$P_{in} = 10^{\frac{P_s+G}{10}-3} \tag{1}$$

where G is the gain of the power amplifier (PA). The two isolators are used to protect the VNA 1 and PA by reducing the reflections. Then the amplified signal is put into the cavity through the probe, which the probe is made by a coaxial cable structure. When the TEM wave comes into the cavity through the coaxial cable, the formation of coaxial probe current will motivate with pattern of electric field parallel to their direction of probe, and when the electric field of the resonant mode and incentive mode electric field of the probe are in the same direction, the cavity resonant mode will be excited or coupled. Due to the incomplete matching between the probe and the resonator, partial signal reflection will occur when the stimulus signal reaches the probe. The value of the

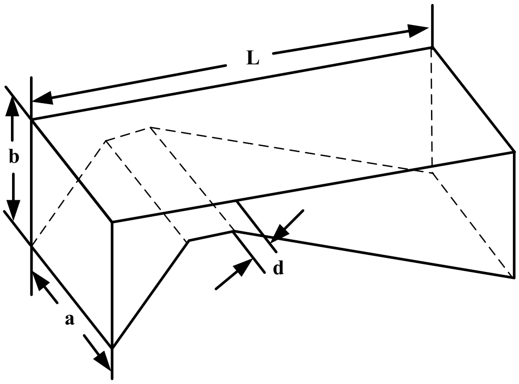

FIGURE 2. **Structure of the compressed cavity.**

reflection (P_{return}) can be measured by the VNA 1 through the directional coupler, expressed as:

$$P_{return} = P_{in} \cdot 10^{\frac{S_{21}}{10}} \tag{2}$$

where S_{21} contains the information about the stimulus signal. Considering that the power level of the measurement signal is always small with weak coupling characteristics, the influence of measurement signal on the electromagnetic field intensity in the cavity can be ignored. Therefore, the actual power injected into the cavity is as follow:

$$P_{in\_real} = P_{in} - P_{return} \tag{3}$$

The relationship between the power injected into the cavity and the maximum electric field intensity in the cavity can be written as [11],

$$E_{\max} = C \cdot \sqrt{P_{in\_real}} \tag{4}$$

where C is the conversion coefficient between power and field intensity, which is related to the cavity structure and geometric size.

B. CAVITY PERTURBATION METHOD

In this paper, the dielectric properties of four typical materials are investigated, whose permeabilities are assumed to be $\mu_r = 1$. Therefore, the dielectric properties of materials can be acquired by the following cavity perturbation equations [26]–[30]:

$$\varepsilon' = \frac{2(\omega_0 - \omega)}{\omega_0} \cdot \frac{\int_{V_c} \vec{E} \cdot \vec{E_0}^* dV}{\int_{V_s} \vec{E} \cdot \vec{E_0}^* dV} + 1 \tag{5}$$

$$\varepsilon'' = \left(\frac{1}{Q} - \frac{1}{Q_0}\right) \cdot \frac{\int_{V_c} \vec{E} \cdot \vec{E_0}^* dV}{\int_{V_s} \vec{E} \cdot \vec{E_0}^* dV} + 1 \tag{6}$$

where ε' and ε'' are the real and imaginary parts of the complex permittivity, respectively. ω_0 and ω are the angular resonant frequency before and after the perturbation, respectively. Q_0 and Q are the quality factor with and without the test sample, respectively. Vs and Vc are the volumes of sample and the cavity, respectively. $\vec{E}$ and $\vec{E_0}$ are the electric field vectors inside the perturbing sample and the unperturbed cavity, respectively.

In order to prevent the test sample from contaminating the resonator and protect the working environment of the resonator, the test sample usually needs to be loaded into a quartz tube, and then placed into the resonant cavity, where the electric field is strong for perturbation. In addition, the effect of quartz tube on the test of sample should be excluded. Then the above perturbation formula needs to be further modified to obtain the dielectric properties accurately. In addition, the volume of the sample is very small relative to the volume of the cavity, which meets the perturbation condition $V_s \ll V_c$ very well. Therefore, the field outside the sample is assumed unchanged, i.e., $\vec{E} = \vec{E_0}$. Finally, equation (5) and (6) can be rewritten as follows:

$$\varepsilon' = \frac{2(\omega - \omega_0)}{\omega_0} \cdot \frac{\int_{V_c} \vec{E_0} \cdot \vec{E_0}^* dV + (\varepsilon'_{tube} - 1) \int_{V_{tube}} \vec{E_0} \cdot \vec{E_0}^* dV}{\int_{V_s} \vec{E_0} \cdot \vec{E_0}^* dV} + 1 \tag{7}$$

$$\varepsilon'' = \left(\frac{1}{Q} - \frac{1}{Q_0}\right) \cdot \frac{\int_{V_c} \vec{E_0} \cdot \vec{E_0}^* dV + (\varepsilon''_{tube} - 1) \int_{V_{tube}} \vec{E_0} \cdot \vec{E_0}^* dV}{\int_{V_s} \vec{E_0} \cdot \vec{E_0}^* dV} + 1 \tag{8}$$

where V_{tube} is the volume of the quartz tube and ε'_{tube} and ε''_{tube} are the real and imaginary parts of the complex permittivity of the quartz tube. Based on these two equations, the dielectric properties of the materials can be acquired accurately.

III. EXPERIMENT AND DISCUSSION

The resonator used in this paper is a compressed rectangular cavity (Fig. 2), whose conversion coefficient can be estimated as follow [11]:

$$C = \sqrt{\frac{8 \cdot Q_c}{\varepsilon_0 a d L \omega_0}} \tag{9}$$

where a and L is the width and the height of the compressed part of the cavity, respectively. d is the height of the compressed part of the cavity. ε_0 is the free space dielectric constant, ω_0 is the angular resonance frequency of the cavity, Q_c is the loading quality factor of the cavity. By combining equations (1) $\sim$ (4) and (9), the microwave field strength around the material in the cavity is calculated. The cavity parameters are as follows: $a = 83.36$ mm, $b = 43.18$ mm, $d = 10$ mm, $L = 155$ mm.

The response curves of each modes of the compressed cavity and the electromagnetic field distribution of the TE_{102} mode and TE_{103} mode are shown in Fig.3. TE_{103} mode is used for measurement of the dielectric property of the sample and TE_{102} mode works as the mode of stimulus signal. It can be seen that the electric field strength of TE_{102} mode in the compression region (sample loading region) is significantly stronger than that in other regions of the cavity. Moreover,

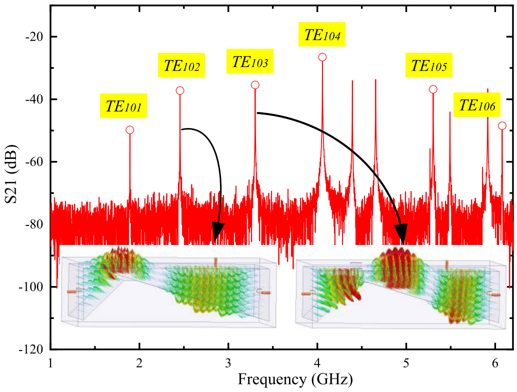

FIGURE 3. Response curves of each modes and the electromagnetic field distribution of modes TE_{102} and TE_{103}.

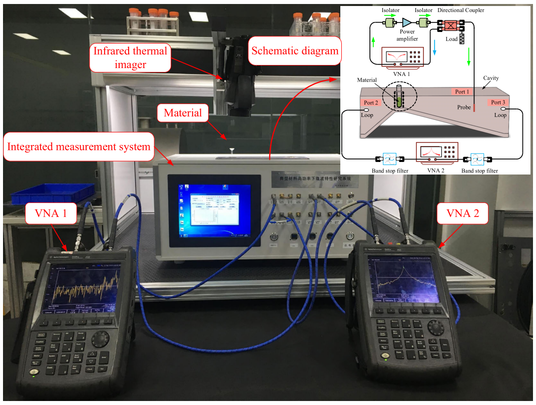

FIGURE 4. The integrated measurement system.

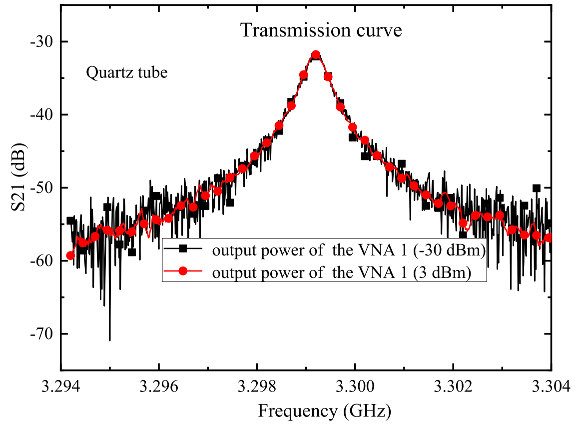

FIGURE 5. Test results of the quartz tube under the given power range.

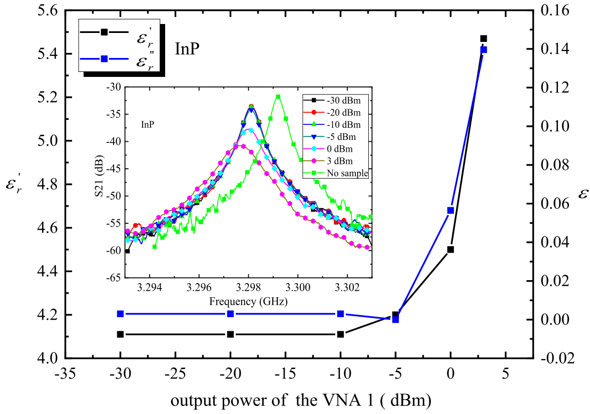

FIGURE 6. Test results of the indium phosphide sample.

the electric field intensity of TE_{103} mode in the compressed region is also very strong. Therefore, after loading the sample at the compressed region, the electronic field strength of TE_{103} mode could be disturbed effectively, and the dielectric property of the sample can be measured accurately.

Based on the compressed cavity and the proposed measurement model (Fig. 1), the integrated measurement system is established, as shown in Fig.3. It should be emphasized that the stimulus signal is provided by the VNA 1, whose frequency is around the working frequency of TE_{102} mode (around 2.45 GHz). The measurement signal is provided by VNA 2, whose frequency is the same as TE_{103} mode (around 3.3 GHz) of the cavity. Dielectric property measurement is performed on four typical materials: indium phosphide (InP), gallium arsenide (GaAs), aluminium oxide (Al_2O_3), and boron nitride (BN).

Since the samples to be tested were all loaded into the resonant cavity through the quartz tube, the effect of the quartz tube on the test results should be excluded first. The quartz tube was placed at the compressed part of the resonant cavity, and the VNA 1 was set to output a narrow and low power signal (−30dBm), whose center frequency is the same as that of the TE_{102} mode. Then set the VNA 2 to output the testing signal, whose frequency is the same as that of the TE_{103} mode. Through two loops, the testing signal can extract the resonator parameters of the cavity and show on the VNA 2, as the black curve shown in Fig. 5. Rest the output of the VNA 1 from −30dBm to 3dBm, the black curve changes to the red curve, as shown in Fig.5. It can be seen that the dielectric properties of the quartz tube did not change in the given power range. Therefore, the quartz tube can be used to load the samples to be test for the experiment. According to the above research method, the dielectric performance of the four materials under different microwave field intensity is obtained and shown in Fig.5 ∼ Fig.8, respectively. These figures all show the variation of the specific resonator parameters under different microwave power and the evolution law of complex dielectric constant of the samples are calculated by the algorithm shown as the equation (7) and (8).

It can be clearly seen from Fig. 6 ∼ Fig. 9 that the dielectric properties of indium phosphide and gallium arsenide have a significant nonlinear evolution characteristic with the change of the microwave field intensity in the cavity. However, the dielectric properties of aluminium oxide and boron nitride remain almost unchanged under the given power range. At the beginning, we speculated that the above phenomenon may be caused by microwave heating, which are mainly related to the loss characteristics of materials. That is to say, the loss of InP and GaAs samples should be greater than that of the Al_2O_3 and BN samples at the measurement frequency

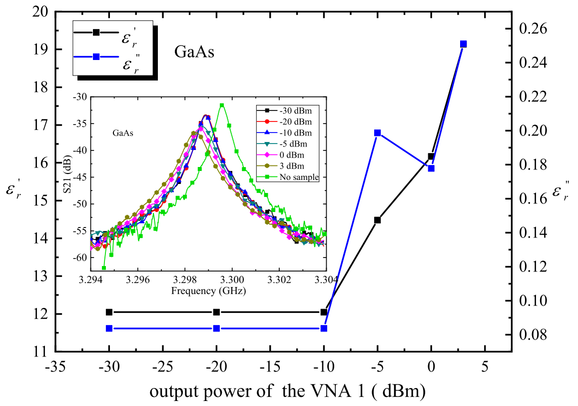

FIGURE 7. Test results of the gallium arsenide sample.

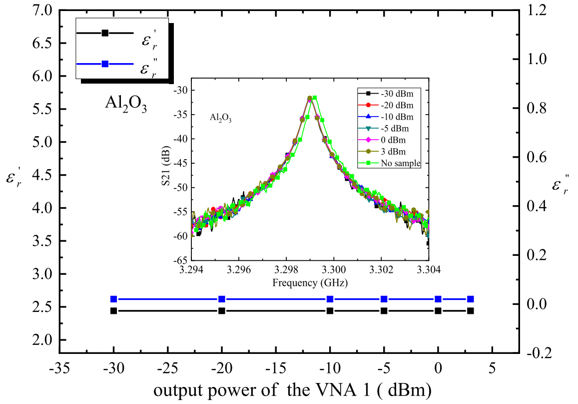

FIGURE 8. Test results of the aluminium oxide sample.

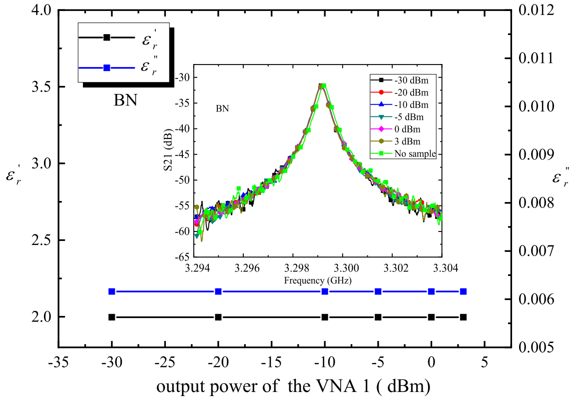

FIGURE 9. Test results of the boron nitride sample.

(around 3.3 GHz). In order to investigate the reason of the above behaviors, two more experiments were carried out in this paper.

Firstly, the complex dielectric constants of the four materials are obtained through the classical cylindrical cavity perturbation method at room temperature with the same frequency as the measurement signal (around 3.3 GHz). Measurement results are shown in Table 1.

From the measurement data in Table 1, it is easy to see that the loss of the indium phosphide sample is obviously smaller than that of the aluminium oxide and boron nitride samples. In other words, the microwave field in the experiment should have a greater impact on the temperature of boron nitride and aluminium oxide in theory. With that said, if the microwave heating is the main reason for the nonlinear dielectric behavior, the experimental results in this paper should be exactly opposite to those obtained. Therefore, it is preliminarily believed that the nonlinear evolution characteristics of dielectric properties of InP and GaAs materials caused by microwave heating are not established, which should be caused by some other mechanism, which may have nothing to do with microwave thermal effect.

TABLE 1. Dielectric property parameters of the material under test (around 3.3GHz, room temperature).

Material	ε'	ε''	$\tan(\varepsilon''/\varepsilon')$
InP	4.11	3.0×10^{-3}	7.31×10^{-4}
GaAs	10.77	6.72×10^{-3}	6.24×10^{-4}
Al_2O_3	2.44	3.0×10^{-3}	2.02×10^{-4}
BN	1.99	6.16×10^{-2}	3.09×10^{-3}

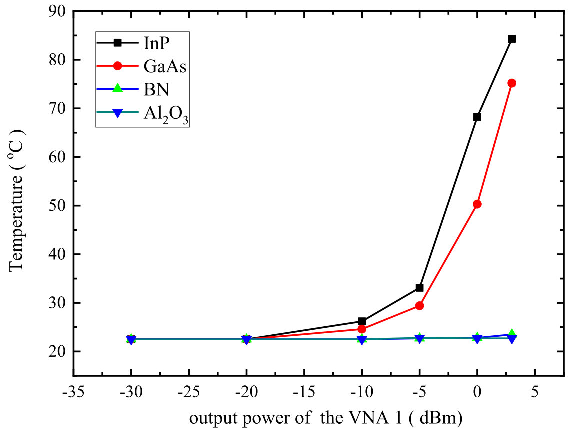

FIGURE 10. Temperature variation of the sample under different stimulus microwave power.

To further validate our conclusion, another experiment is conducted. In the experiment, an infrared thermal imager is used to monitor the accurate temperature of the sample under the given different stimulus microwave power, as is shown in Fig. 4. The temperature variation of the sample under different stimulus microwave power is obtained and shown in Fig. 10. It is easy to find that the InP and GaAs samples have has a nonlinear temperature rising characteristics within the studied power range, and the temperature variation ranges from room temperature to about $80°C$, not exceeding $90°C$. However, the temperature of the Al_2O_3 and BN samples in the experiment did not change more than $2°C$. Here gives two points description about the temperature acquisition: (1) in reference [31], the temperature is detected from the quartz tube, and the sample temperature is obtained by calibration algorithm. In this paper, we obtain the temperature of the sample directly; (2) from the Fig.6 in [31], we can find that the surface temperature and the body temperature of the

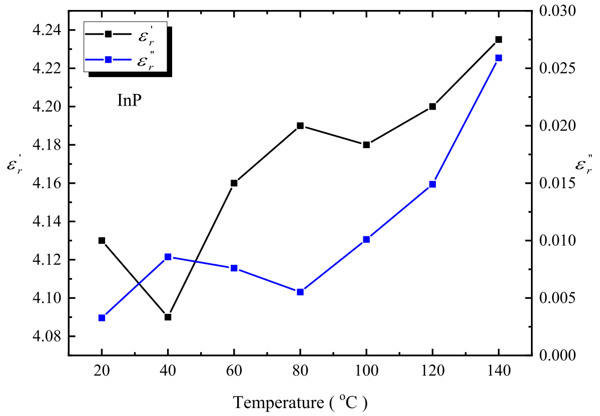

FIGURE 11. **Dielectric properties of InP samples vary from room temperature to 140°*C*.**

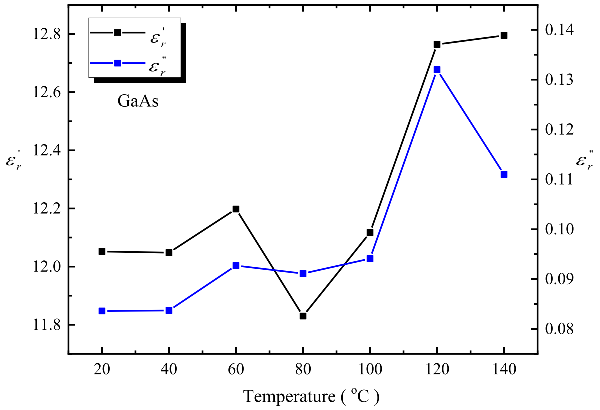

FIGURE 12. **Dielectric properties of GaAs samples vary from room temperature to 140°*C*.**

sample are of highly consistency in the low temperature zone (less than 200°*C*). Therefore, the temperature obtained by the above method is reliable.

In order to confirm that whether the nonlinear variation of dielectric properties of InP and GaAs are caused by temperature rising, the temperature characteristics of dielectric properties of InP and GaAs were experimentally studied, ranging from room temperature to 140°*C*. The measurement results are shown in Fig. 11 and Fig. 12.

In Fig.11, it can be seen that the real part of dielectric constant of InP sample changes by no more than 2.5%, and the imaginary part changes by no more than 5 times within the range of room temperature to 140°*C*. However, the test results of InP under the action of high power microwave (as is shown in Fig.6)show that the real part of dielectric constant of the sample changes by more than 30%, and the imaginary part changes by more than 40 times, both of which are significantly higher than the test results shown in Fig.11. Similar phenomenon can be seen from Fig.12 and Fig.7. In Fig.12, the real part of dielectric constant of GaAs sample changes by no more than 6%, and the imaginary part changes by no more than 1.5 times within the range of room temperature to 140°*C*. However, from Fig.7, it can be seen that the real part of dielectric constant of the sample changes by more than 50%, and the imaginary part changes by more than 40 times, both of which are significantly higher than the test results shown in Fig.12. That is to say, the effect of high power microwave on the dielectric properties of InP sample cannot be explained simply by microwave thermal effect, and there should be some inherent interaction mechanism between high power microwave and the InP materials, which is called the microwave non-thermal effect.

IV. CONCLUSION

This contribution reflects on the reliability of the traditional dielectric property evaluation method brought by the continuous development of high power microwave technology and microwave millimeter wave technology, and puts forward a method for solving the evolution rules of dielectric property of materials under the action of strong microwave field. The specific implementation mainly includes the following aspects: Firstly, four typical kinds of low loss materials were experimentally studied by the established system, and the evolution rules of their dielectric properties with external field intensity was obtained. Then, the dielectric properties of the four samples were compared, which preliminarily determine that the existence of microwave non-thermal effect. Finally, by comparing the evolution law of the dielectric properties of InP and GaAs under the action of high power microwave and the temperature characteristics of dielectric properties under weak microwave field, we further proves that the nonlinear evolution characteristics of the dielectric properties of InP and GaAs under the strong microwave field environment is not only related to the microwave thermal effect, which may be related to the existence of the microwave non-thermal effect. What's more, the experimental method and system constructed in this paper can provide some technical support for the measurement and characterization of dielectric properties of materials under the environment of strong microwave field.

REFERENCES

[1] J. R. Laghari and A. N. Hammoud, "A brief survey of radiation effects on polymer dielectrics," *IEEE Trans. Nucl. Sci.*, vol. 37, no. 2, pp. 1076–1083, Apr. 1990.

[2] S. A. Komarov, A. S. Komarov, and D. G. Barber, "Open-ended coaxial probe technique for dielectric spectroscopy of artificially grown sea ice," *IEEE Trans. Geosci. Remote Sens.*, vol. 54, no. 8, pp. 4941–4951, Aug. 2016.

[3] W. Barry, "A broad-band, automated, stripline technique for the simultaneous measurement of complex permittivity and permeability," *IEEE Trans. Microw. Theory Techn.*, vol. MTT-34, no. 1, pp. 80–84, Jan. 1986.

[4] A. M. Paz, S. Trabelsi, S. O. Nelson, and E. Thorin, "Measurement of the dielectric properties of sawdust between 0.5 and 15 GHz," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 10, pp. 3384–3390, Oct. 2011.

[5] E. Kilic, U. Siart, O. Wiedenmann, U. Faz, R. Ramakrishnan, P. Saal, and T. F. Eibert, "Cavity resonator measurement of dielectric materials accounting for wall losses and a filling hole," *IEEE Trans. Instrum. Meas.*, vol. 62, no. 2, pp. 401–407, Feb. 2013.

[6] A. Verma and D. C. Dube, "Measurement of dielectric parameters of small samples at X-band frequencies by cavity perturbation technique," *IEEE Trans. Instrum. Meas.*, vol. 54, no. 5, pp. 2120–2123, Oct. 2005.

[7] K. Han, M. Swaminathan, R. Pulugurthan, H. Sharma, R. Tummala, B. M. Rawlings, and V. Nair, "RF characterization of magnetodielectric material using cavity perturbation technique," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 5, no. 12, pp. 1850–1859, Dec. 2015.

[8] V. V. Rostov, I. V. Romanchenko, and M. S. Pedos, "Superradiant Ka-band Cherenkov oscillator with 2-GW peak power," *Phys. Plasmas*, vol. 23, no. 9, Sep. 2016, Art. no. 093103.

[9] E. Juntunen, D. Dawn, S. Pinel, and J. Laskar, "A high-efficiency, high-power millimeter-wave oscillator using a feedback class-E power amplifier in 45 nm CMOS," *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 8, pp. 430–432, Aug. 2011.

[10] H. Zhu, Y. Yang, X. Zhu, Y. Sun, and S.-W. Wong, "Miniaturized resonator and bandpass filter for silicon-based monolithic microwave and millimeter-wave integrated circuits," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 65, no. 12, pp. 4062–4071, Dec. 2018.

[11] Y. Gao, E. Li, G. Guo, and H. Zheng, "Experimental investigation on the interaction mechanism between microwave field and semiconductor material," *IEEE Access*, vol. 6, pp. 41921–41927, 2018.

[12] Y. Gao, E. Li, and C. Yu, "Nonlinear dielectric property of InP under strong microwave field," *AIP Adv.*, vol. 8, no. 10, Oct. 2018, Art. no. 105229.

[13] J. Hoydis, M. Kobayashi, and M. Debbah, "Green small-cell networks," *IEEE Veh. Technol. Mag.*, vol. 6, no. 1, pp. 37–43, Mar. 2011.

[14] H.-R. Sun and K.-M. Huang, "A novel microwave cancellation circuit for measuring nonlinear dielectric changes of polar solution under microwave fields," *J. Phys. D, Appl. Phys.*, vol. 48, no. 47, Dec. 2015, Art. no. 475502.

[15] J. Miyakoshi, "Cellular and Molecular responses to radio-frequency electromagnetic fields," *Proc. IEEE*, vol. 101, no. 6, pp. 1494–1502, Jun. 2013.

[16] H. R. Sun and K. M. Huang, "Experimental study of dielectric property changes in DMSO-primary alcohol mixtures under low-intensity microwaves," *RSC Adv.*, vol. 5, no. 75, pp. 61031–61034, Jun. 2015.

[17] M. Zielinski and M. Krzemieniewski, "The effect of microwave electromagnetic radiation on organic compounds removal efficiency in a reactor with a biofilm," *Environ. Technol.*, vol. 28, no. 1, pp. 41–47, Jan. 2010.

[18] G. Grainaru, T. S. Sudarshan, and S. A. Gradinaru, "Electrical properties of high resistivity 6H-SiC under high temperature/high field stress," *Appl. Phys. Lett.*, vol. 70, no. 6, pp. 735–737, Feb. 1997.

[19] M. Hosseini, N. Stiasni, and V. Barbieri, "Microwave-assisted asymmetric organocatalysis. A probe for nonthermal microwave effects and the concept of simultaneous cooling," *J. Org. Chem.*, vol. 72, no. 4, pp. 1417–1424, Feb. 2007.

[20] M. A. Herrero, J. M. Kremsner, and C. O. Kappe, "Nonthermal microwave effects revisited: On the importance of internal temperature monitoring and agitation in microwave chemistry," *J. Org. Chem.*, vol. 73, no. 1, pp. 36–47, Jan. 2007.

[21] R. O. Bolt and J. G. Carroll, *Radiation Effects on Organic Materials*. New York, NY, USA: Academic, 1963, pp. 657–658.

[22] P. Alexander, A. Charlesby, and J. H. Kim, "Energy transfer in macromolecules exposed to ionizing radiations," *Nature*, vol. 173, no. 4404, pp. 578–579, Mar. 1954.

[23] L. A. wall and D. W. Brown, "Chemical activity of gamma-irradiated polymethyl methacrylate," *J. Res. Nat. Bureau Standards*, vol. 57, no. 3, pp. 131–136, Sep. 1956.

[24] A. Chapiro, *Radiation Chemistry of Polymeric Systems*. New York, NY, USA: Wiley, 1962, pp. 1799–1807.

[25] I. Kuriyama, N. Hayakawa, Y. Nakase, J. Ogura, H. Yagyu, and K. Kasai, "Effect of dose rate on degradation behavior of insulating polymer miaterials," *IEEE Trans. Electr. Insul.*, vol. EI-14, no. 5, pp. 272–277, Oct. 1979.

[26] Y. Yu, E. Li, and G. Gao, "Dielectric characterisation of small samples using broadband coaxial cavity," *Electron. Lett.*, vol. 53, no. 19, pp. 1316–1318, Sep. 2017.

[27] A. Kik, "Complex permittivity measurement using a ridged waveguide cavity and the perturbation method," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 11, pp. 3878–3886, Nov. 2016.

[28] R. G. Cater, "Accuracy of microwave cavity perturbation measurement," *IEEE Trans. Microw. Theory Techn.*, vol. 49, no. 5, pp. 918–923, May 2001.

[29] J. Sheen, "Amendent of cavity perturbation technique for loss tangent measurement at microwave frequencies," *J. Appl. Phys.*, vol. 102, no. 1, Jul. 2007, Art. no. 014102.

[30] A. W. Kraszewski and S. O. Nelson, "Observations on resonant cavity perturbation by dielectric objects," *IEEE Trans. Microw. Theory Techn.*, vol. 40, no. 1, pp. 151–155, Jan. 1992.

[31] B. García-Baños, J. J. Reinosa, F. L. Peñaranda-Foix, J. F. Fernández, and J. M. Catalá-Civera, "Temperature assessment of microwave-enhanced heating processes," *Sci. Rep.*, vol. 9, Jul. 2019, Art. no. 10809.

YONG GAO received the Ph.D. degree in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China, (UESTC), Chengdu, China, 2019. He is currently working as a Postdoctoral Researcher in electromagnetic fields and microwave technology with UESTC. His research interests include nonlinear dielectric properties of high-power microwave material, interaction mechanism between high power microwave and materials, high-power devices feature parameter extraction, passive intermodulation test technology, design of microwave devices, and microwave integrated circuits.

EN LI received the M.S. degree in physical electronics and the Ph.D. degree in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China, Chengdu, China, in 2003 and 2009, respectively. In 1997, he joined the Faculty of the University of Electronic Science and Technology of China. From 2005 to 2010, he was an Associate Professor, where he was involved in research projects in the area of electro-magnetic parameters measurement of materials, design of microwave device design, automatic microwave test system. Since 2010, he has been a Professor. He is currently a Guest Professor with the National Defense Science and Technology Key Lab of Advanced Function Composite Material. He has taken charge of the research projects in the area of electromagnetic parameters measurement of dielectric materials at high temperatures and microwave plasma diagnosis. He has authored or coauthored over 100 journals and conference papers. He has 22 authorized national invention patents. His current main research interests include microwave plasma diagnosis, electromagnetic parameter measurement of dielectric material at high temperature and high power microwave field, interaction mechanism between high-power microwave and materials, nonlinear parameter measurement of high power amplifier, and design of microwave devices. He is also a member of the Standing Council of the National Materials New Technology Development Research Institute. He was a recipient of the Second Prize of National Science and Technology Progress Award, the First, Second, and Third Prize of Provincial and Ministerial Level Scientific and Technological Progress Awards and Title of Excellent Experts with Outstanding Contribution of Sichuan Province, in 2013. He was the winner of Education Ministry's New Century Excellent Talents Supporting Plan, in 2010, and the Reserve Candidate of Academic and Technical Leader of Sichuan Province, in 2013. In 2018, he won the First Prize for National Defense Technology Invention. He was awarded the Zhuoqing Talent Program, in 2019.

GAOFENG GUO received the M.S. and Ph.D. degrees in physical electronics from the University of Electronic Science and Technology of China, Chengdu, China, in 2000 and 2008, respectively. In 2000, she joined the Faculty of the University of Electronic Science and Technology of China. From 2001 to 2006, she was a Lecturer, where she was involved with research projects in the area of electromagnetic parameter measurement of microwave dielectric material. Since 2006, she has been an Associate Professor, where she has been involved in research projects in the area of electromagnetic parameters measurement of dielectric materials, dielectric property measurement at high temperatures. Her current research interests include electromagnetic parameter measurement of dielectric material, and nonlinear parameter measurement of high-power amplifier.

HU ZHENG received the M.S. degree in optics from Xidian University, Xi'an, China, in 2005, and the Ph.D. degree in electronic engineering from the University of Chinese Academy of Sciences, Beijing, China, in 2008. He is currently an Associate Professor with the University of Electronic Science and Technology of China. His current research focuses on microwave imaging, indirect holography, microwave measurement theory, electromagnetic inverse scattering, nonlinear dielectric of microwave material, and nonlinear measurement.

YANG ZHOU received the B.S, M.S., and the Ph.D. degrees in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China, Chengdu, China, in 2005, 2008, and 2011, respectively. He is currently an Associate Professor working with the College of Communication Engineering, Chengdu University of Information Technology. His major research interests include electro-magnetic parameters measurement of materials, nonlinear parameter measurement of high-power amplifier, and microwave device.