
# 云南大学无线创新实验室

## 论文集

黄铭 杨晶晶 黎鹏 编著

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# 内容简介

论文集收录了云南大学无线创新实验室2006~2015年发表的27篇SCI收录的英文论文，这些文章都经过了严格的盲审，英文表达是过关的。论文集收录的文章内容涉及面广，研究工作具有创新性。全书共分为27个主题，每个主题对应1篇SCI收录论文。

论文涉及微波与物质相互机理、传感、天线和超材料调控电磁场的方法。在微波与物质相互机理方面，论文“A New Equation for the Description of the Dielectric Losses Under Microwave Irradiation”导出了微波与物质相互作用的新方程，揭示了材料弛豫特性的重要性，扩展了电磁波的应用领域；论文“Modeling the Dielectric Response in Heterogeneous Materials Using 3D RC Networks”证明了颗粒材料弛豫频率与其等效电阻电容的关系；论文“Graphene Sandwiches as a Platform for Broadband Molecular Spectroscopy”和“Broadband Molecular Sensing with a Tapered Spoof Plasmon Waveguid”进一步证明，在太赫和红外频段上述结论同样成立。在传感方面，论文“Microwave Sensor for Measuring the Properties of a Liquid Drop”测量了液滴的动态特性，是国内最早得到*Nature China*的摘要和评述的论文之一；论文“Microwave Cavity Perturbation Technique for Measuring the Moisture Content of Sulphide Minerals Concentrate”测量了矿物的水分；论文“Metamaterial Sensors”是超材料传感器方面的第一篇综述性论文，其他论文还有“Modelling and Analysis of Ω-Shaped Double Negative Material-Assisted Microwave Sensor”“Double Negative Metamaterial Sensor Based on Microring Resonator”“Simulation and Analysis of a Metamaterial Sensor Based on a Microring Resonator”“Experimental Verification of a Metamaterial Open Resonator”“Surface WGM Sensor Based on a Cylindrical Dielectric Waveguide”和“A Spoof Surface WGM Sensor Based on a Textured PEC Cylinder”。传感器应用和控制的论文是“Information Fusion-Based Storage and Retrieve Algorithms for WSNs in Disaster Scenarios”和“Hierarchical MAS Based Control Strategy for Microgrid”。在天线方面，论文“General Considerations for the Miniaturization of Radiative Antennae”提出了设计小型化天线的方法，结果表明采用超材料可将半波振子天线的长度缩小为原来的1/10；其他三篇论文“Directive Emission Obtained by Mu and Epsilon-Near-Zero Metamaterials”“Design of Multi-Beam Antennas Based on Epsilon-Near-Zero Metamaterials”和“Mu and Epsilon Near Zero Metamaterials for Perfect Coherence and New Antenna Designs”涉及近零超材料在天线设计中的应用。在超材料调控电磁场方面，论文“Reciprocal Invisibility Cloak Based on Complementary Media”设计了交互式斗篷，与Pendry斗篷不同，我们设计的斗篷能看到外面的场景；涉及超材料调控电磁场的论文

还有“Metamaterial Electromagnetic Concentrators with Arbitrary Geometries”“Electromagnetic Concentrators with Arbitrary Geometries Based on Laplace’s Equation”“Transparent Device with Homogeneous Material Parameters”“An External Cloak with Arbitrary Cross Section Based on Complementary Medium and Coordinate Transformation”“Cylindrical Electromagnetic External Cloak with Only Axial Material Parameter Spatially Variant”“A Novel Method for Designing Electromagnetic Shrinking Device with Homogeneous Material Parameters”和“Manipulating the Field Distribution of a Polygonal SPP Resonator Based on AZIM”。

论文集可供从事电子工程、通信工程、微波理论与技术等相关专业的高年级学生、研究生、教师和工程技术人员参考。同时，论文集可供研究生撰写英文论文时学习参考。

# 实验室简介

云南大学无线创新实验室（http://www.winlab.ynu.edu.cn）是云南大学与云南省无线电监测中心联合共建成立的。

近年来，依托于云南大学无线创新实验室和信息学院等单位，先后申报成立了“昆明市谱传感与无线电监测重点实验室”（云南大学第一个昆明市重点实验室）和“云南省高校谱传感与边疆无线电安全重点实验室”；与天津大学合作建立了“云南省叶声华院士工作站”（云南IT领域第一个院士工作站）。以这些条件平台为基础，在云南大学怀周楼建立了国内高校第一个多功能的无线电公共安全预警监测站，该监测站是国家和云南省无线电监测网的重要组成部分，担负着频谱资源管理、云南大学及周边区域的无线电公共安全和各类考试保障任务。同时，该监测站也是上述科研平台的建设内容之一，是云南大学无线创新实验室在边疆无线电安全领域进行理论和技术创新的重要场所，也是云南大学承担社会责任、服务地方经济建设和社会发展的体现。监测站的建设使云南大学翠湖校区的无线电安全保障技术和设施居国内高校领先水平。

云南大学无线创新实验室以“信息与通信工程一级学科博士学位授权点”和“博士后科研流动站”为支撑(云南IT领域第一个博士点和博士后流动站)，依托于云南大学信息学院等单位建设。实验室主要从事谱传感、无线电监测、无线通信信号处理、网络通信、超材料与微波技术应用的研究，是一个集学术研究、人才培养、技术咨询、产品开发和系统集成于一体的学术团队。实验室拥有省级学术带头人3人、云南省有突出贡献优秀专业技术人员和省委联系专家1人。近年来，实验室发表了SCI刊源论文100余篇，其中一篇得到了*Nature China*的摘要和评述；实验室成员参与申报的项目获得国家技术发明二等奖、主持申报的项目先后获得云南省自然科学二等奖1项、科技进步奖3项；实验室成员承担了多项国家自然科学基金和省部级科研项目，其中，实验室博士后（云南IT领域第一个自主培养的博士后)获得了“中国博士后基金第53批面上项目”和“中国博士后基金第七批特别资助”（云南大学史上第七个获得特别资助者）。实验室与国内外学者有广泛的合作和学术交流，2014年，伦敦帝国理工大学Blackett Lab.的Yan Francescato 博士来实验室访问，并在*ACS Photonics*、*Optics Express*杂志上合作发表了多篇研究论文。

# 目　录

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# A new equation for the description of dielectric losses under microwave irradiation

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**Abstract**
A new equation was developed to describe quantitatively the dielectric loss of materials that is a key parameter in the fields of microwave chemistry and microwave processing of materials under microwave irradiation. This equation can be applied to explain the complicated thermal runaway phenomenon that has relations with dielectric relaxation and to simulate the dielectric loss under microwave irradiation. It was also found that the simulation results based on this equation are in good agreement with the Volge–Fulcher law. The new equation has potential application in the study of microwave interaction with solid materials, especially in materials' processing which involves microwave chemistry, synthesis, sintering, melting, joining, surface-modifications, quality improvements, etc and it is hoped that the dynamic process of material under microwave irradiation could be explained.

## 1. Introduction

Since the early 1980s, microwaves have been widely used in chemistry [1–3] and also used to process a wide variety of absorbing materials [4–8]. A few possible mechanisms were proposed to explain the microwave interaction with absorbing materials. An initial explanation was the rotation of polar molecules [9]. The molecular dipoles are induced by microwave to rotate. This rotation causes molecular collisions that generate heat. Unfortunately this mechanism does not explain the intensity of the observed microwave effects. Other possible mechanisms are superheating effects [10], formation of hot spots [11], the presence of ionic molecules [12], photochemical focus [13] and the induction losses caused by eddy current [14]. However, mechanistic details of these microwave-driven processes are still far from understood, particularly, since few theoretical calculation was conducted to simulate these dynamic processes.

On the other hand, for polar molecules, the traditional approach [15] to the interpretation of the frequency dependence of the dielectric loss is based on the Debye relaxation mechanism for which the time domain response is given by

$$F(t) = \exp(-t/\tau), \tag{1}$$

where $\tau$ and $t$ are relaxation time and observation time, respectively.

The dielectric loss does not obey equation (1) except in some liquid dielectrics and departs seriously from it in most solids [16–18]. It is shown that some relaxation processes, particularly, chemical reaction kinetics, would follow the time domain response law [19]:

$$F(t) = \exp[-\left(\frac{t}{\tau}\right)^{\alpha}] \qquad 0 < \alpha < 1. \tag{2}$$

While $\alpha$ equals 0.5, $F(t)$ is called slow relaxation, the slow response [20] or non-Debye relaxation for which the relaxation mechanism is governed by the bound charges. Equation (2) was obtained in the absence of microwave irradiation, and it is very important to develop an equation, which can be used to

calutate the dielectric loss of non-Debye dielectric relaxation under microwave irradiation. However, so far there is no report on the equation that need to find.

Here we report that an equation was deduced to calculate the dielectric loss mechanism for non-Debye dielectric relaxation. To the best of our knowledge, this seems to be the first equation used to describe the non-Debye relaxation phenomena in solids under microwave irradiation. Based on this equation and experimental results, which are the relation between the imaginary permittivites ($\varepsilon''$) and temperature of two different materials, we simulated the relation between relaxation time $\tau$ and temperature of these materials. More interestingly, the simulation results indicate that the relation between dielectric relaxation time $\tau$ and temperature of the materials is in good agreement with the Volge–Fulcher law [17].

The new equation successfully explained the thermal runaway phenomenon of material under microwave irradiation. Based on this equation, the higher the temperature of material is, the smaller the relaxation time $\tau$ will be, and more power will be absorbed by the material. The equation also has potential application in the study of microwave interaction with solid materials, especially in sintering of important ceramics, processing of metallic materials, microwave-assisted organic synthesis, nano-chemistry, etc. Moreover, the dynamic process of material under microwave irradiation could be explained using the equation.

## 2. Dielectric loss computation methods

### *2.1. Dielectric loss per unit volume*

From Maxwell's differential equations, Ohm's loss in dielectric medium of materials is given by

$$\int_v \vec{E}\cdot\vec{J}\,\mathrm{d}v = \int_v \vec{E}\cdot\left(\nabla\times\vec{H} - \frac{\partial\vec{D}}{\partial t}\right)\mathrm{d}v$$

$$= \int_v \left[\vec{H}\cdot(\nabla\times\vec{E}) - \nabla\cdot(\vec{E}\times\vec{H}) - \vec{E}\cdot\frac{\partial\vec{D}}{\partial t}\right]\mathrm{d}v.$$

Taking time derivatives of $\vec{E}\cdot\vec{D}$ and $\vec{H}\cdot\vec{B}$, we have

$$\frac{\partial}{\partial t}(\vec{E}\cdot\vec{D}) = \vec{E}\cdot\frac{\partial\vec{D}}{\partial t} + \vec{B}\cdot\frac{\partial\vec{E}}{\partial t},$$

$$\frac{\partial}{\partial t}(\vec{H}\cdot\vec{B}) = \vec{H}\cdot\frac{\partial\vec{B}}{\partial t} + \vec{B}\cdot\frac{\partial\vec{H}}{\partial t}.$$

Finally, we obtain

$$\oint_s (\vec{E}\times\vec{H})\mathrm{d}s = \int_v \left[\vec{H}\cdot\frac{\partial\vec{B}}{\partial t} + \vec{E}\cdot\frac{\partial\vec{D}}{\partial t} + \vec{E}\cdot\vec{J}\right]\mathrm{d}v$$

$$= \int_v \left[\frac{1}{2}\frac{\partial}{\partial t}(\vec{E}\cdot\vec{D}) + \frac{1}{2}\frac{\partial}{\partial t}(\vec{H}\cdot\vec{B})\right]\mathrm{d}v + \int_v \vec{E}\cdot\vec{J}\,\mathrm{d}v$$

$$+ \int_v \left[\frac{1}{2}\left(\vec{E}\cdot\frac{\partial\vec{D}}{\partial t} - \vec{D}\cdot\frac{\partial\vec{E}}{\partial t}\right)\right]\mathrm{d}v$$

$$+ \int_v \left[\frac{1}{2}\left(\vec{H}\cdot\frac{\partial\vec{B}}{\partial t} - \vec{B}\cdot\frac{\partial\vec{H}}{\partial t}\right)\right]\mathrm{d}v.$$

The term on the left-hand side of this equation represents the power flowing on closed surface $s$. The first term on the right-hand side represents the electric energy and magnetic energy stored within the volume $v$. The second term on the right-hand side represents the power dissipated within the volume $v$. The third term on the right-hand side represents electric losses of material within the volume $v$. The fourth term on the right-hand side represents the magnetic losses of material within the volume$v$. Therefore, for electric dielectric material, the dielectric loss per unit volume is

$$P_d = \frac{1}{2}\left(\vec{E}\cdot\frac{\partial\vec{D}}{\partial t} - \vec{D}\cdot\frac{\partial\vec{E}}{\partial t}\right), \tag{3}$$

where $\vec{E}$ is electric field intensity vector, in $\mathrm{V\,m^{-1}}$, $\vec{H}$ is magnetic field intensity vector, in $\mathrm{A\,m^{-1}}$, $\vec{D}$ is electric flux density vector, in $\mathrm{C\,m^{-2}}$, $\vec{B}$ is magnetic flux density vector, in $\mathrm{Wb\,m^{-2}}$, $\vec{J}$ is volume current density vector, in $\mathrm{A\,m^{-2}}$ and the volume $v$ is bounded by the surface $s$.

### *2.2. Debye dielectric relaxation*

If Debye dielectric relaxation mechanism is followed and governed by equation (1) and the process occurring under an electric field with $E(t) = E\cos\omega t$ would still follow the linear superposition principle, we obtain

$$D(t) = \varepsilon_h E(t) + \varepsilon_l \int_{-\infty}^{t} E(t')\frac{\partial}{\partial t}\left[-\exp\left(-\frac{t-t'}{\tau}\right)\right]\mathrm{d}t'$$

$$= \varepsilon'(\omega)E\cos(\omega t) - j\varepsilon''(\omega)\sin(\omega t),$$

$$P_\mathrm{d} = \frac{1}{2}E\cos(\omega t)\frac{\partial}{\partial t}[\varepsilon'(\omega)E\cos(\omega t) - j\varepsilon''(\omega)E\sin(\omega t)],$$

$$P_\mathrm{d} = \tfrac{1}{2}\varepsilon'' E^2\omega, \tag{4}$$

where $P_\mathrm{d}$ is the dielectric loss per unit volume based on the Debye relaxation, $\varepsilon_\mathrm{h}$ is the high frequency permittivity of the material, $\varepsilon_\mathrm{l}$ is the low frequency permittivity or static permittivity of the material, $\varepsilon'(\omega)$ is the real part of the dielectric permittivity of the material and $\varepsilon' = \varepsilon_\mathrm{h} + \varepsilon_\mathrm{l}/(1+\omega^2\tau^2)$, $\varepsilon''(\omega)$ is the imaginary part of the dielectric permittivity of the material and $\varepsilon'' = \omega\tau\varepsilon_\mathrm{l}/(1+\omega^2\tau^2)$, the electric field $E(t)$ is switched on at $t = t'$ and $\omega$ is the angular frequency of microwave.

Equation (4) indicates that the dielectric loss per unit volume is in agreement with the traditional law [8].

### *2.3. Non-Debye relaxation*

If non-Debye dielectric relaxation mechanism is followed and governed by equation (2) and the other conditions are the same as 2.2, we obtain

$$D(t) = \varepsilon_\mathrm{h}E(t) + \varepsilon_\mathrm{l}\int_{-\infty}^{t} E(t')\frac{\partial}{\partial t}\{-\exp[-\sqrt{(t-t')/\tau}]\}\,\mathrm{d}t'$$

$$= \varepsilon_\mathrm{h}E(t) + \frac{\varepsilon_\mathrm{l}E}{2\tau}\int_{-\infty}^{t}\cos(\omega t')\left(\frac{t-t'}{\tau}\right)^{-1/2}$$

$$\times\exp[-\sqrt{(t-t')/\tau}]\,\mathrm{d}t'$$

$$= \varepsilon_t' E\cos(\omega t) + \varepsilon_t'' E\sin(\omega t),$$

$$P_t = \frac{1}{2}E^2\omega\varepsilon_t'' + \frac{E^2}{2}\left(\cos^2(\omega t)\frac{\partial\varepsilon_t'}{\partial t} + \cos(\omega t)\sin(\omega t)\frac{\partial\varepsilon_t''}{\partial t}\right), \tag{5}$$

where

$$\varepsilon_t' = \varepsilon_h + \frac{\varepsilon_l}{2\tau}\int_0^\infty \left(\frac{t''}{\tau}\right)^{-1/2}\exp(-\sqrt{t'/\tau})\cos(\omega t'')\,dt'',$$

$$\varepsilon_t'' = \frac{\varepsilon_l}{2\tau}\int_0^\infty \left(\frac{t''}{\tau}\right)^{-1/2}\exp(-\sqrt{t'/\tau})\sin(\omega t'')\,dt''$$

$$t'' = t - t'$$

and $P_t$ is the dielectric loss per unit volume based on the non-Debye relaxation.

Comparing equations (4) and (5), the first term on the right-hand side of equation (5) is a little similar to equation (4), but $\varepsilon_t''$ is different from $\varepsilon''$, and the second term on the right-hand side of equation (5) is a function of $t$ and $\partial/\partial t$. Therefore, the dynamic processes of non-Debye dielectric under microwave irradiation could be simulated using equation (5).

## 3. Results and discussion

The dielectric loss per unit volume $P_d$ in equation (4) is a time independent quantity, while $P_t$ in equation (5) is a function of $t$ and $\tau$. The characteristic of material under power microwave irradiation is variable, which is the foundation of microwave chemistry and materials' processing. Therefore, equation (5) could be used to explain the dynamic processes under power microwave irradiation.

The frequency of microwave irradiation is 2460 MHz, the interaction between material and microwave is about $2.46\times10^9$ times per second and temperature rise of the material under microwave irradiation is less than 0.1 °C per second [21]; therefore, the electric dielectric characteristic of the material is invariable within less than a second, and we can get that $\partial\varepsilon_t'/\partial t$ and $\partial\varepsilon_t''/\partial t$ is equal to zero, respectively.

Substituting $\partial\varepsilon_t'/\partial t = 0$ and $\partial\varepsilon_t''/\partial t = 0$ into equation (5) would yield

$$P_t = \tfrac{1}{2}E^2\omega\varepsilon_t''(\tau, t). \tag{6}$$

Using equation (6), the dependence of the power absorbed by material on time $t$ at different $\tau(\tau_1 > \tau_2 > \cdots > \tau_i > \tau_{i+1})$ is shown in figure 1, which indicates that the smaller the relaxation time$\tau$, the greater the power absorbed by the material.

Figure 2 shows the imaginary permittivites ($\varepsilon''$) of nickeliferous limonitic laterite ores measured by Pickles [22] at frequencies of 2460 MHz at temperature up to about 1000 °C using the cavity perturbation technique.

It can be seen from figure 2 that imaginary permittivites ($\varepsilon''$) of nickeliferous limonitic laterite increases while the temperature is increasing, and $\varepsilon''$ is the function of temperature, which can be written as $\varepsilon''(T)$. Therefore, it can be obtained from equation (4) that the power absorbed by material increases while the temperature is increasing. The temperature of nickeliferous limonitic laterite is a function of irradiation time, and $T = g(t)$, then using equation (4) the microwave power absorbed by dielectric would be directly proportion to $\varepsilon''(T)$:

$$P_d = \tfrac{1}{2}\varepsilon''(T)E^2\omega. \tag{7}$$

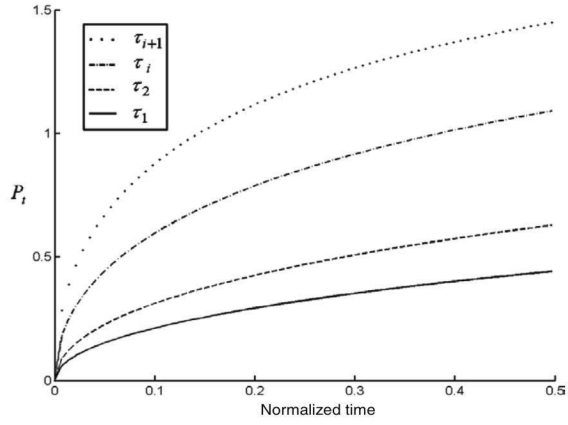


**Figure 1.** The dependence of the power absorbed by dielectric on the normalized time.

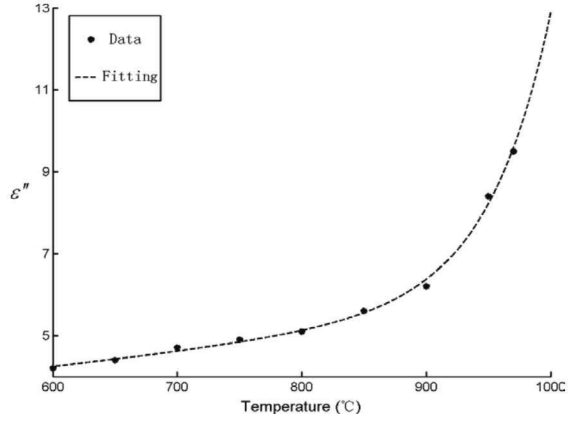


**Figure 2.** The imaginary permittivities ($\varepsilon''$) of nickeliferous limonitic laterite as a function of temperature at 2460 MHz. ●, data from [22]; dashed line is the fitting curve.

In order to use equation (6) to explain the power absorbed by nickeliferous limonitic laterite under microwave irradiation, we suppose that equation (6) is directly proportional to equation (7) with a coefficient $k$, and we have

$$\varepsilon_t''(\tau, t) = k\varepsilon''(T). \tag{8}$$

Supposing that time $t_1, t_2, \ldots, t_9$ is corresponding to 600 °C, 650 °C, …, 1000 °C, respectively, and dielectric relaxation time $\tau$ is invariable in the time interval $\Delta t(\Delta t \to 0)$, then from equation (8), the followings can be obtained:

$$\frac{\varepsilon_l}{2\tau_1}\int_{t_1}^{t_1+\Delta t}\left(\frac{t-t_1}{\tau_1}\right)^{-1/2}\exp(-\sqrt{(t-t_1)/\tau_1})dt = k\varepsilon''(600),$$

$$\frac{\varepsilon_l}{2\tau_2}\int_{t_2}^{t_2+\Delta t}\left(\frac{t-t_2}{\tau_2}\right)^{-\frac{1}{2}}\exp[-\sqrt{(t-t_2)/\tau_2}]dt = k\varepsilon''(650),$$

$$\vdots$$

$$\frac{\varepsilon_l}{2\tau_9}\int_{t_9}^{t_9+\Delta t}\left(\frac{t-t_9}{\tau_9}\right)^{-\frac{1}{2}}\exp[-\sqrt{(t-t_9)/\tau_9}]dt = k\varepsilon''(1000),$$

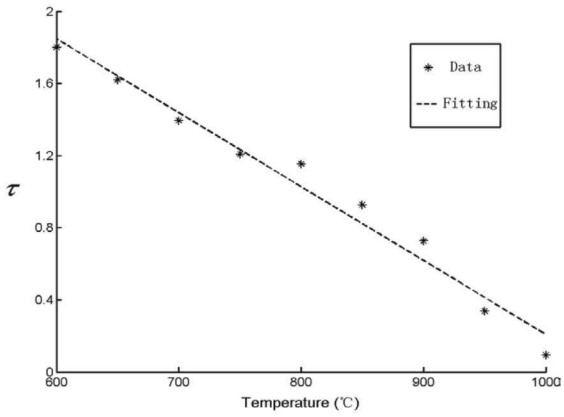


**Figure 3.** Simulation result of relaxation time versus the temperature of nickeliferous limonitic laterite. ∗, the value of relaxation time from simulation; dash–dot line is the fitting curve.

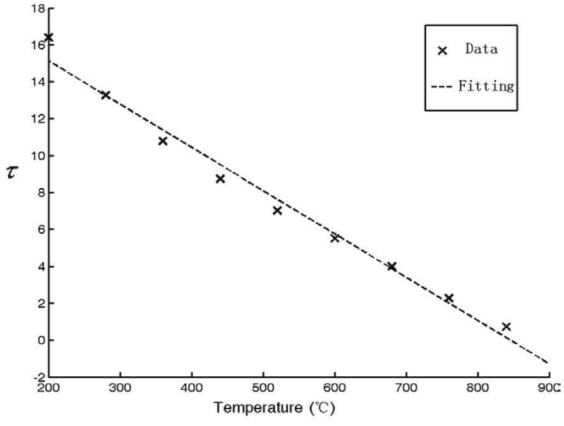


**Figure 4.** Simulation result of relaxation time versus the temperature of alumina. ×, the value of relaxation time from simulation; dashed line is the fitting curve.

where $\tau_1, \tau_2, \ldots, \tau_9$ is the relaxation time that is corresponding to microwave irradiation time $t_1, t_2, \ldots, t_9$, respectively.

Solving the preceding equations by any standard method, we obtain the relation between relaxation time$\tau$and temperature $T$ showed in figure 3.

Using the same simulation procedure and the experimental result of dielectric loss in alumina as a function of temperature that had been measured by Westphal and Sils [23], the relation between relaxation time and the temperature of alumina was also obtained and shown in figure 4.

In the two examples above, the simulation results show that the relaxation time $\tau$ is inversely proportional to temperature, which is in good agreement with the Vogle–Fulcher law, and is confirmed by the good linear fit.

## 4. Conclusions

(1) It was found that under sinusoidal microwave irradiation the dielectric response is not sinusoidal again, the response of non-Debye dielectric time dependent power absorbed by the dielectric exists and the power absorbed by material between 0–$\tau$ is variable.

(2) The results calculated using equation (6) are in good agreement with the Vogle–Fulcher law, which show that the relaxation time $\tau$ has an inverse ratio to the temperature of the material.

(3) The new equation has potential application in the study of the microwave interaction with solid materials, and it is hoped that the dynamic processes of material under microwave irradiation could be explained.

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Technical note

# Microwave cavity perturbation technique for measuring the moisture content of sulphide minerals concentrates

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**Abstract**

The moisture content of a sulphide mineral concentrate was measured by the microwave cavity perturbation technique. Comparative experiments were performed using this technique and by oven drying. It was found that the deviation in the measurement of the moisture content of the concentrate was less than 0.5%, indicating that this would be a suitable technique for moisture content determination of sulphide mineral concentrates.


*Keywords:* Sulphide ores; On-line analysis; Modelling; Microwave resonator; Moisture content

## 1. Introduction

Moisture determination has been a major problem in many branches of industry for many years. In the metallurgical industry, the exact moisture content of a specified material has to be determined in order to allow control of the water dosage, of the quality of the product, and of the reduction of applied energy.

Moisture determination by microwaves is applied in many branches of industry (Kraszewski, 1996). However, few applications (Cutmore et al., 2000; Klein, 1981) have been reported in the metallurgical industry. It has been shown that the penetration depth of microwaves is much greater than that of infrared radiation, and microwave methods can measure the volume moisture content of the materials. In addition, microwave methods are much safer and faster than ionizing radiation methods (Kupfer, 2005).

The objective of this paper is to apply the microwave cavity perturbation technique (Carter, 2001; Harrington, 1961) for the rapid measurement of the moisture content of sulphide mineral concentrates containing sphalerite, chalcopyrite and nickel sulphide minerals.

## 2. Experimental techniques

### 2.1. Materials

Three different materials, sphalerite concentrate, chalcopyrite concentrate, and nickel sulphide concentrate were used in the microwave moisture determination experiments. These samples were obtained from a smelter in Yunnan (China). The composition of the sphalerite concentrate was: Fe 7.24%; $SiO_2$ 3.48%; S 28.47%; Zn 50.18% other elements 10.63%, respectively. The composition of the chalcopyrite concentrate was: S 31.13%; Fe 30.17%; Cu 20.10%; Zn 2.99%; $SiO_2$ 5.28%; Ni 0.012%; Pb 0.63%; Bi 0.09%; $Al_2O_3$ 0.68%; CaO 0.44%; MgO

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0.39%; As 0.56%, respectively. The composition of the nickel sulphide concentrate was Ni 2.86%; Cu 2.36%, respectively.

### 2.2. Measuring equipment

The mechanism for this technique is the measurement of resonant frequency and the output voltage of the resonant sensor (Radmanesh, 2002) unloaded and loaded with samples, as resonant frequency and output voltage of the resonant sensor are very sensitive to moisture content.

The main parts of the equipment include resonant sensor (Huang et al., 2002), sweeping signal, detector and DSP, interface circuit, and computer. The software control of the set-up was performed by Windows XP operating system, and programmed by Visual Basic 6.0.

### 2.3. Method

To obtain the samples with different moisture content, each sulphide concentrate (typically 5 kg in weight) was dried at 105 °C for at least 2 h, and the samples of the three different concentrates were each divided into 10 shares, every share weighing 0.5 kg. Subsequently, samples with different moisture content were obtained by adding different proportions of water. Finally, the moisture contents of the samples were obtained by putting the samples into the resonant sensor one by one.

## 3. Results and discussion

A series of 10 tests were carried out with sphalerite concentrates of different moisture content, the testing time per sample being about 5 s. The results are plotted as a function of moisture content in Fig. 1. It can be seen that the output voltage of the resonant sensor decreases as the moisture content increases. Interestingly, their relationship follows a nonlinear fitting equation: $V = -0.0007x^2 - 0.0385x + 2.0497$. The resonant frequency of the resonant sensor shows a gradually decrease as moisture content increases, and follows a nonlinear fitting equation: $f = -0.0004x^2 + 0.0010x + 2.4250$, where $x$ is the moisture content of the samples. Based on the fitting equation, the measurement deviation of sphalerite concentrates is less than 0.42%. Using the same method, the measurement deviations of chalcopyrite concentrates and nickel sulphide concentrates are less than 0.37% and 0.41%, respectively.

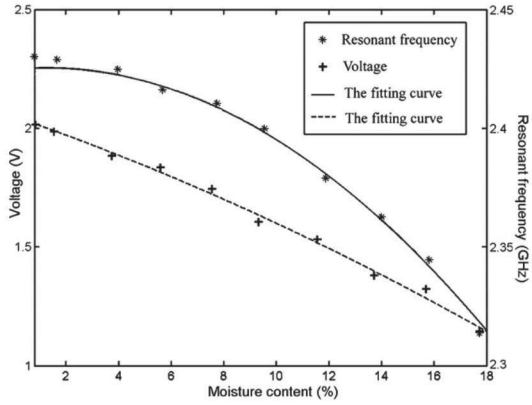


Fig. 1. Plot of output voltage and resonant frequency of the resonant sensor against moisture content of sphalerite concentrates.

Microwave cavity perturbation measurement is an indirect technique, which must be calibrated against a reference method (e.g. oven drying) for different materials. The initial temperature of the material influences the measured moisture content of the material, so the temperature at set-up and the material needs to be compensated for. Generally, the natural inhomogeneity of the samples used (particularly at large particle sizes) influences the moisture content measurement, and it is difficult to assess accurately the moisture content of the sample (Cutmore et al., 2000). However, for sulphide mineral concentrates used in our experiments, the particle sizes were smaller than 0.07 mm, so that this did not affect the measured results.

## 4. Conclusions

(1) Using the microwave cavity perturbation technique, it is possible to determine the moisture content of sulphide mineral concentrates.
(2) The measurement deviation is less than 0.5% under laboratory conditions.
(3) The commercial prototype of the microwave cavity perturbation technique for measuring the moisture content of sulphide mineral concentrates is now under development (Huang et al., 2005) and patents are pending.

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# Microwave sensor for measuring the properties of a liquid drop

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**Abstract**
A novel microwave sensor for measuring the properties of a liquid drop has been invented, its analytical theory established and a working prototype has been constructed and tested. It was also found that the theory based on the microwave sensor is in good agreement with the experimental results. Excellent linearity is achieved by optimizing the design, with an accuracy of distilled water drop volume measurement of approximately 0.5 $\mu$l, and this microwave sensor has been used to measure surface tension, species concentration and the microwave absorption properties of a liquid drop simultaneously, which are the key parameters in the fields of physical chemistry and microwave chemistry.

**Keywords:** liquid drop, microwave sensor, surface tension, absorption properties

## 1. Introduction

The formation of drops is a phenomenon ubiquitous in daily life, science and technology [1]. It is found that a great deal of information on liquid properties is contained in the process of drop formation. This makes it possible to measure several physical parameters of a liquid by using drop analysis. The development of a fibre drop multianalyser has been reported over the last 15 years [2]. It has proved to be a powerful analytical tool for determining the physical and chemical characteristics of liquids. More recently, capacitive tensiography has been reported [3, 4]. It has been demonstrated that the capacitive transducer gives a direct measurement of the volume in the pendant liquid drop, with a resolution of 1 $\mu$l.

It is well known that microwave and infrared form a continuous electromagnetic spectrum that extends from RF frequency to optical wave. It has been shown that the RF capacitive sensor and fibre sensor can measure the parameters of a liquid drop [2, 3]. Therefore, it is possible to measure the parameters of a liquid drop by a microwave sensor. The objective of this paper is to apply the microwave sensor for the measurement of the parameters of a liquid drop. Preliminary experiments have been carried out and these show that the microwave sensor is capable of measuring drop volumes with an accuracy of down to 0.5 $\mu$l. It can also measure microwave absorption properties, species concentration and surface tension simultaneously.

## 2. Theory

Microwave sensors based on cavity perturbation techniques have been studied by many researchers [5, 6]. Measurements of a liquid drop are performed by inserting a small, appropriately shaped liquid drop into a cavity and determining the properties of the liquid drop from the resultant change in the resonant frequency and loaded quality factor which is given by [7]

$$f_0 - f_s = \frac{1}{2}(\varepsilon_r' - 1) f_s W_0^{-1} \int_{vs} E \cdot E_0^* \, \mathrm{d}v \tag{1}$$

$$Q_s^{-1} - Q_0^{-1} = \frac{1}{2} W_0^{-1} \varepsilon_r'' \int_{vs} E \cdot E_0^* \, \mathrm{d}v. \tag{2}$$

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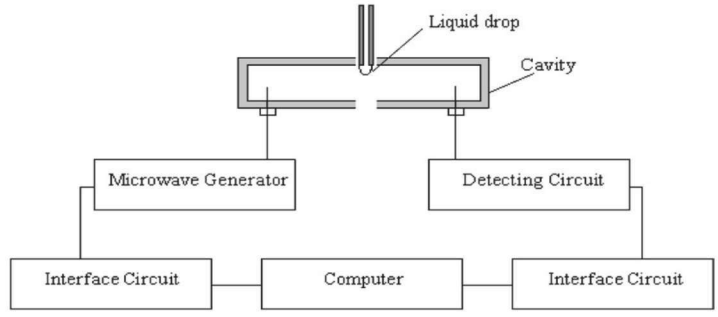


**Figure 1.** Sketch of the microwave sensor for measuring the properties of a liquid drop.

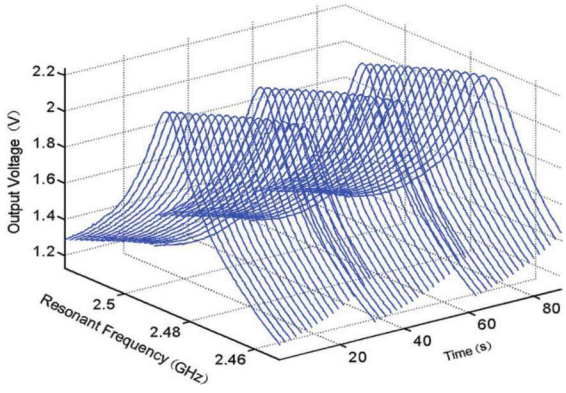


**Figure 2.** 3D graph detected by the microwave sensor in the process of the formation of three distilled water drops.

Here $\varepsilon_r = \varepsilon_r' - \mathrm{j}\varepsilon_r''$ is the complex permittivity of the liquid drop; $\varepsilon'$ and $\varepsilon''$ are the real part and the imaginary part; $E_0$ is the field in the unperturbed cavity and $E$ is the field in the interior of the liquid drop; $v_s$ is the volume of the liquid drop; $Q_0$ and $f_0$ are the quality factor and resonance frequency of the cavity in the unperturbed condition respectively and $Q_s$, $f_s$ the corresponding parameters of the cavity loaded with the liquid drop; $W_0$ is the total energy stored in the cavity.

Under the quasi-static approximation, the electric field within a liquid drop sphere placed in a uniform external electric field $E_0$ is given by [8]

$$E = \frac{3E_0}{\varepsilon_r' + 2}. \tag{3}$$

Substitution of this expression into (1) yields the usual expression for the perturbation of the frequency by a small liquid drop sphere,

$$\Delta f = f_0 - f_s = \frac{3E_0^2(\varepsilon_r' - 1)f_s}{2W_0(\varepsilon_r' + 2)} \cdot V_s(t), \tag{4}$$

where $V_s(t)$ is the volume of the liquid drop which grows in the process of drop formation. Equation (4) indicates that the resonant frequency change $\Delta f$ of the cavity is directly proportional to $V_s(t)$.

The microwave cavity is a two-port network. The insertion loss and half power width of this network can be written as [9]

$$T = \frac{2\sqrt{\beta_1\beta_2}}{1 + \beta_1 + \beta_2} \tag{5}$$

$$Q_s = \frac{f_s}{B} \tag{6}$$

where $T$ is the insertion loss of the network, and $T = (P_{\text{in}} - P_{\text{out}})/P_{\text{in}}$. $P_{\text{in}}$ and $P_{\text{out}}$ are the microwave input power and the microwave output power of the cavity respectively. $\beta_1$ and $\beta_2$ are the input coupling coefficient and the output coupling coefficient of the network respectively, and $\beta_1 = Y_{01}/n_1^2G$, $\beta_2 = Y_{02}/n_2^2G$. $Y_{01}$ is the equivalent input admittance of the network. $Y_{02}$ is the equivalent output admittance of the network. $n_1$ and $n_2$ are the turns ratio of the input ideal transformer and the turns ratio of the output ideal transformer, respectively. $G$ is the equivalent conductance of the networks. $B$ is the half power width of the network.

Suppose that $n_1$, $n_2$, $Y_{01}$, $Y_{02}$ are constant, and $R = 1/G = k\varepsilon_r'' V_s(t)$, where $R$ is directly proportional to $V_s(t)$ with a coefficient $k$, $\beta_1 \ll 1$, $\beta_2 \ll 1$, then from equation (5), the following can be obtained

$$\begin{aligned} P_{\text{out}} &= 1 - \frac{2\sqrt{\beta_1\beta_2}}{1 + \beta_1 + \beta_2} \cdot P_{\text{in}} \\ &\approx 1 - 2\sqrt{\beta_1\beta_2} \cdot P_{\text{in}} \\ &= 1 - \frac{2P_{\text{in}}\varepsilon_r'' k\sqrt{Y_{01}Y_{02}}}{n_1 n_2} \cdot V_s(t) \\ &= 1 - \frac{2P_{\text{in}}k'\varepsilon_r''}{n_1 n_2} \cdot V_s(t) \end{aligned} \tag{7}$$

where $k' = k\sqrt{Y_{01}Y_{02}}$. Equation (7) indicates that the larger the volume $V_s(t)$ of the liquid drop, the smaller the output power $P_{\text{out}}$ of the cavity. Therefore, the smaller the $P_{\text{out}}$, the smaller the output voltage of the cavity, and the output voltage of the cavity is inversely proportional to $V_s(t)$.

Substituting equation (3) into (2) would yield

$$Q_s^{-1} = Q_0^{-1} + \frac{3\varepsilon_r'' E_0^3}{2W_0(\varepsilon_r' + 2)} \cdot V_s(t). \tag{8}$$

Equation (8) indicates that the larger $V_s(t)$ is, the smaller $Q_s$ will be, and $Q_s$ of the cavity is inversely proportional to $V_s(t)$.