Measurement of the Dielectric Constant and Loss Tangent of High Dielectric-Constant Materials at Terahertz Frequencies

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***Abstract*—Low-loss high dielectric-constant materials are analyzed in the terahertz frequency range using time-domain spectroscopy. The dielectric constant and loss tangent for steatite, alumina, titania loaded polystyrene, and zirconium–tin–titanate are presented and compared to measurements on high-resistivity silicon. For these materials, the real part of the dielectric constant ranges from 6 to 90. All of the samples were found to have reasonable low-loss tangents. Applications as photonic crystal substrates for terahertz frequency antenna are envisaged.**

***Index Terms*—Antennas, dielectric materials, measurements, submillimeter waves.**

I. Introduction

LOW-LOSS high dielectric-constant materials have many applications in established and cutting-edge terahertz frequency systems. Interest is not limited to laboratory systems, but includes aerospace, automotive, communications, defence, domestic, medical, and marine applications. Furthermore, low-loss dielectric materials are now of increasing importance in the design of circuit components and quasi-optical elements. There is much work in this area, and rapid advances are being made in the development of terahertz sources, detectors, mixers, and similar components. However, the development of functional systems in this frequency range is dependent on the availability of improved components, including attenuators, isolators, modulators, switches, and directional couplers.

Recently, periodic electromagnetic or photonic bandgap (PBG) crystals have provided new impetus to the research into dielectric materials. The topic of PBG crystals is currently one of the most rapidly advancing sectors in electromagnetics, and it has been receiving a great deal of attention in the last ten years. The interest is based on the ability of PBG crystals to control the propagation of electromagnetic waves to an extent that was not previously possible [1]. Following the theoretical demonstration of their feasibility, it took a number of years before a PBG crystal was physically realized.

Many of the technological problems associated with PBG crystals are practical, and usually relate to the method of manufacture. To this end, some ingenious ways of producing such crystals have recently been developed [2], [3]. One key element in the successful operation of these crystals is the dielectric contrast between the constituent materials, and there is a requirement for high-dielectric low-loss dielectric materials in the terahertz-frequency range.

Interest in dielectrics has usually been focused on the real part of the dielectric constant, and on the loss tangent. The problem that is often encountered at the early design phase of integrated or quasi-optical components is the serious shortage of data at terahertz frequencies, as most material characterization is routinely performed only in the megahertz frequency range. Furthermore, there can be significant variations in the measured results, arising from the measurement technique, supplier, or composition of the material (annealing, sintering, impurities, etc.). If data is available, it is very often only at spot frequencies, while for technical reasons, continuous coverage is attractive. In the microwave region, the dielectric characteristics are most often dominated by slowly varying dielectric relaxation. This means that many materials need only be characterized at a few frequencies, but at terahertz frequencies, this does not necessarily hold.

II. Measurement Method and Setup

For broad-band continuous analysis of high dielectric materials, a time-domain terahertz spectroscopy method was chosen [4]–[6]. In contrast to narrow-band conventional heterodyne methods, this technique enables extremely broad-band characterization from 50 GHz up to 43 THz [7]–[9]. Additionally, in contrast to incoherent measurement techniques (e.g., bolometric detection), which detect only the intensity of terahertz radiation, the time-domain approach is intrinsically coherent and, therefore, permits the detection of the amplitude and phase of a terahertz signal. This automatically suppresses the influence of any incoherent noise background, greatly enhancing the detection sensitivity. It also allows the measurement of complex material properties, like the complex dielectric constant,

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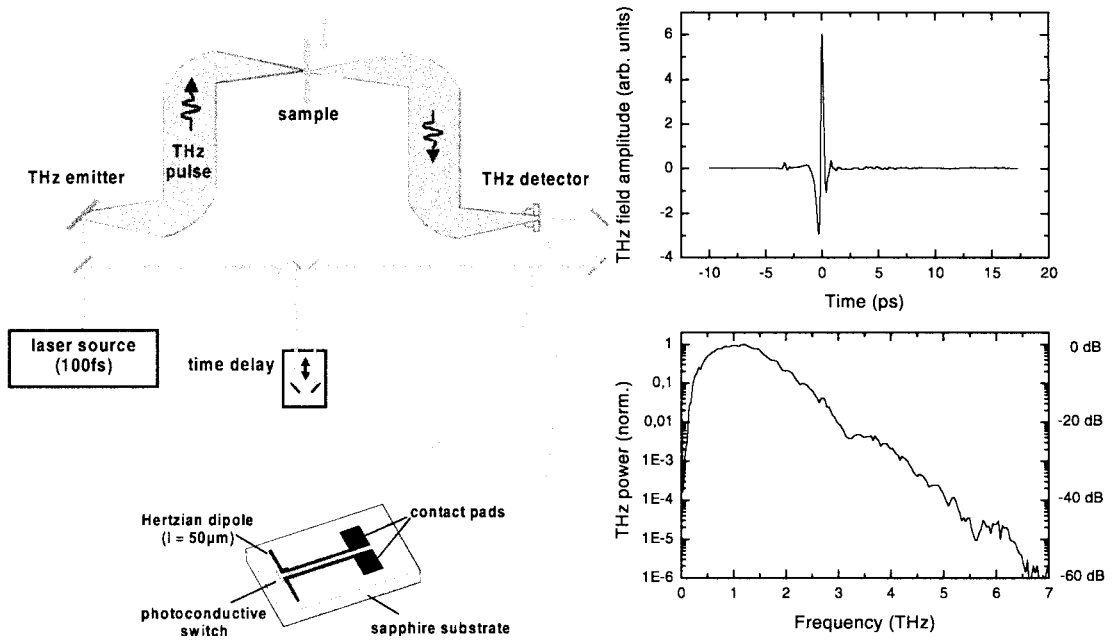

Fig. 1. (*left*) Schematic diagram of an experimental system for time-resolved terahertz spectroscopy. (*right*) Typical terahertz electric field transient and corresponding Fourier spectrum of the employed surface field emitter/photoconductive detector combination.

without requiring the potentially problematic Kramers–Kronig analysis.

The general concept of time-domain terahertz spectroscopy is to make use of ultrashort laser pulses to generate and detect terahertz radiation. Fig. 1 is a schematic diagram of an experimental test system for time-domain coherent terahertz spectroscopy. An ultrashort laser pulse, with duration of typically 10–100 fs, excites a terahertz emitter. The radiated pulse is focused on the sample by a pair of paraboloidal mirrors in order to avoid any dispersion introduced by using lenses. The transmitted terahertz electric field is then guided with a second pair of paraboloids and focused onto a detector. This monitors the electric field at the time it is gated by a second time-delayed laser pulse. The correlation of excitation and detection pulses allows the terahertz electric-field amplitude to be monitored in the time domain.

The time-domain terahertz spectroscopy system used is based on 100-fs optical pulses from a commercial Ti:Al_2O_3 laser operating at a repetition rate of 76 MHz to generate broad-band terahertz pulses by photoexciting charge carriers within the surface field of an epitaxial InGaAs film (for details see [10]). The transmitted terahertz electric field is detected by a photoconductive antenna made from low-temperature grown gallium arsenide [11], with a silicon lens attached for enhanced collection efficiency. The entire system is flushed with dry nitrogen to remove the influence of water absorption. A usable bandwidth between approximately 300 GHz to over 5 THz is obtained, as shown in Fig. 1. The focus size in this setup is 870 μm (full width at half maximum (FWHM) of field amplitude), although lower regions of the spectrum exhibit a diffraction limited focus that is larger.

For the material analysis, reference transient measurements are taken without the sample inserted in the measurement system in order to be able to correct for the spectral dependencies of the system. Transient measurements are then taken, with the sample placed in the terahertz beam path under normal incidence. A series of ten sample and reference measurements is taken to reduce and to quantify experimental errors. The ratio of the complex Fourier transforms of sample $E(\nu)$ and reference $E_{\mathrm{ref}}(\nu)$ signals provides the complex transmissivity $t(\nu)$, which is a direct measure of the complex refractive index $\tilde{n}(\nu) = n(\nu) - ik(\nu)$ of the analyzed sample at the respective frequency ν. Fresnel equations including Fabry–Perot effects yield [12]

$$t(v) = \frac{E(\nu)}{E_{\mathrm{ref}}(\nu)} = \frac{\dfrac{4\tilde{n}}{(\tilde{n}+1)^2} \cdot \exp\left(-i\dfrac{2\pi\nu \cdot (\tilde{n}-1)\cdot d}{c}\right)}{1 - \dfrac{(\tilde{n}-1)^2}{(\tilde{n}+1)^2} \cdot \exp\left(-i\dfrac{4\pi\nu \cdot \tilde{n} \cdot d}{c}\right)} \tag{1}$$

for a slab of material of thickness d. Hence, as the experiments deliver both the real and imaginary components of $t(\nu)$, both the real and imaginary components of $\tilde{n}(v)$ (or other quantities like $\varepsilon_1(\nu)$ and $\varepsilon_2(\nu)$ or $\tan(\delta)$ can directly be determined. Appropriate numerical approaches are described in [13] and [14]. The only source of systematic error in this and, more generally, in any type of terahertz transmission experiments to evaluate dielectric properties, is the difficulty of precisely accounting for scattering effects. As a result of this, a fraction of the terahertz pulses might scatter out of the detection path and, therefore, indicate a larger loss tangent than the true value. Nevertheless, scattering is expected to be small in these experiments, given the large aperture of the detection system (30°) and the homogeneity of the samples on the spatial scale of the applied wavelengths (50 μm–3 mm). Experiments with varying detection apertures confirm this conjecture.

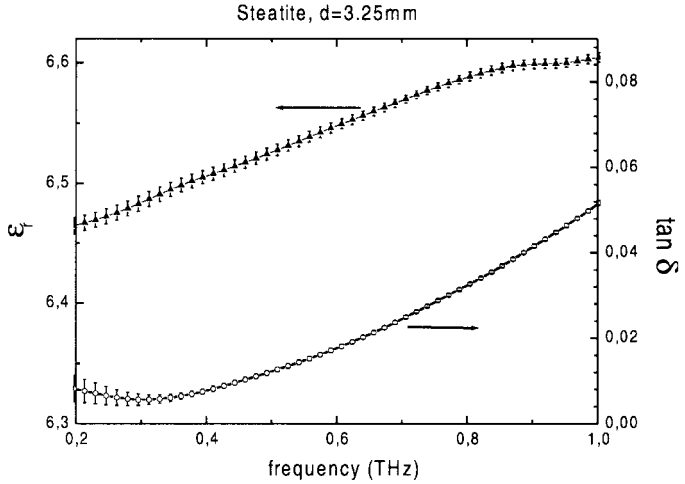

Fig. 2. Average and standard deviation of the real part of the dielectric constant, and loss tangent for the steatite sample.

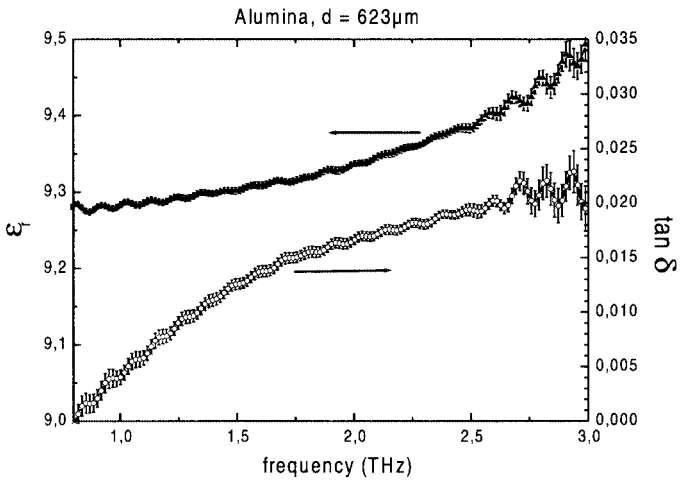

Fig. 3. Average and standard deviation of the real part of the dielectric constant, and loss tangent for the alumina sample.

III. Experimental Results

Several materials were selected, which seem promising for manufacturing terahertz components, given their low cost, simple processing, reproducible parameters, and ready availability. The following four materials, besides silicon, have been measured with dielectric constants ranging from 6 to 90:

1) steatite (real part of epsilon ≈ 6.5);
2) alumina (Al_2O_3, real part of epsilon ≈ 9.7);
3) titania loaded polystyrene (real part of epsilon ≈ 16);
4) two versions of zirconium–tin–titanate (Zr $SnTiO_3$, real part of epsilon ≈ 36 and 90).

Of these materials, alumina is the most common. All dielectric ceramics are nontoxic and nonhazardous and no special handling or storage precautions are required. The higher dielectric-constant materials are slightly granular.

The measured dielectric constants and loss tangents of the samples are shown in Figs. 2–6. Figs. 2–5 show the average and standard deviation for the dielectric constant and loss tangent determined from ten consecutive measurements on individual samples. The error bars constitute, therefore, an indication for all statistical errors of the measurement approach. Fig. 6 shows the average and standard deviation from three nominally identical samples, in order to quantify parameter variations in a set of samples. The reproducibility of the results was confirmed

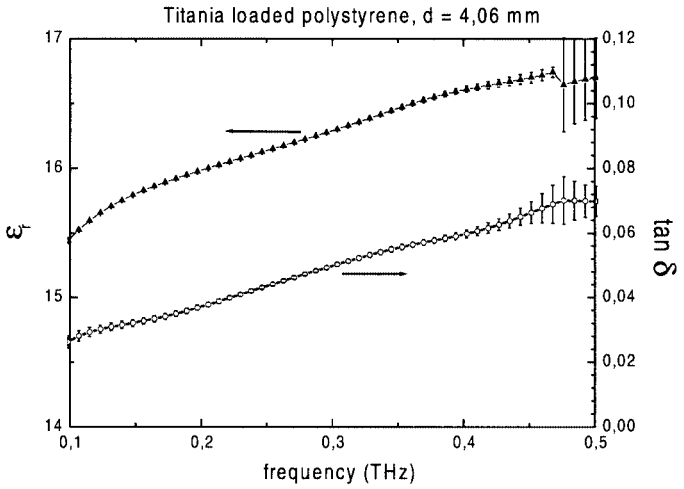

Fig. 4. Average and standard deviation of the real part of the dielectric constant, and loss tangent for the titania in polystyrene matrix sample.

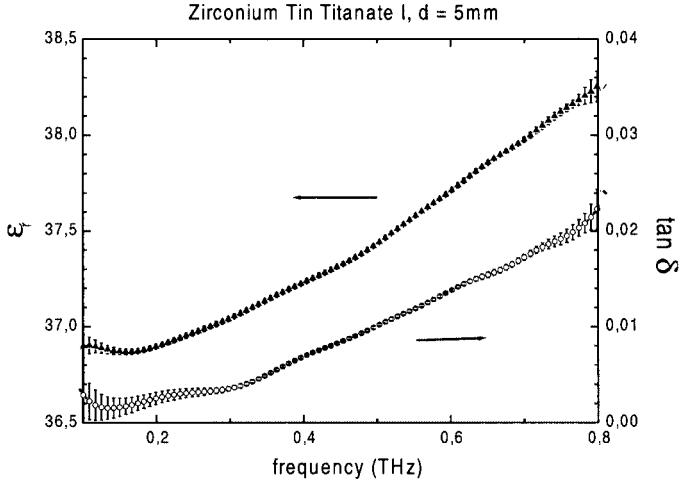

Fig. 5. Average and standard deviation of the real part of the dielectric constant, and loss tangent for the zirconium–tin–titanate I sample ($\varepsilon_r \approx 37$).

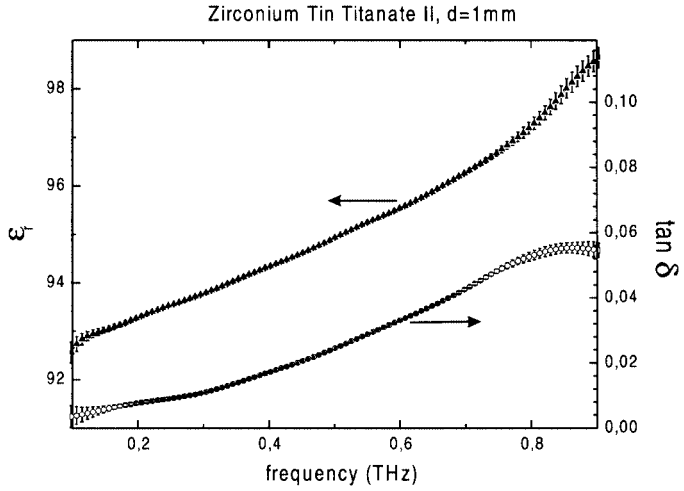

Fig. 6. Average and standard deviation of the real part of the dielectric constant, and loss tangent for a set of three zirconium–tin–titanate II samples ($\varepsilon_r \approx 90$).

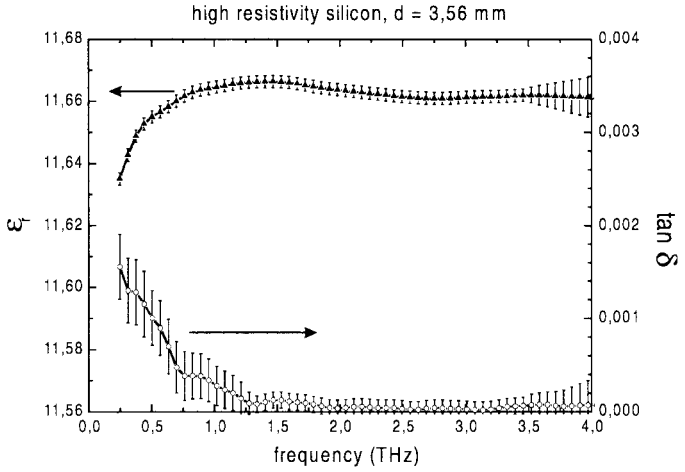

Fig. 7. Average and standard deviation of the real part of the dielectric constant, and loss tangent for the high-resistivity silicon sample.

by repeating the measurements at different sample locations. All samples exhibited a very high homogeneity. Fig. 7 shows measurements performed on high-resistivity crystalline silicon (epsilon $\approx$ 11.6), which, despite of a higher cost, is known to be an excellent dielectric material at terahertz frequencies [15]–[17]. The experiments on silicon were performed in a collimated beam configuration in order to enhance the measurement accuracy and enable the measurement of the extremely low losses of this material.

The presented spectra have varying spectral ranges for the different samples, as only spectral information with an adequate signal-to-noise ratio of greater than 20 dB was taken for evaluating material parameters. Due to the available sample thickness, only a restricted region of the 5-THz system bandwidth was, therefore, utilizable. The measurement accuracy varies accordingly with sample thickness and spectral position. For example, the zirconium–tin–titanate samples presented in Fig. 6 have a standard deviation of 0.13 ‰ (6 ‰) for the real part (or $\tan\delta$) of the dielectric constant observed at the central spectral range, which degrades down to 2 ‰ (43 ‰) at the spectral edges of the measurement bandwidth. The data quality of this three-sample average indicates not only the adequacy of the experimental approach, but also excellent sample homogeneity. Most samples show a nearly linear positive dependence on frequency of both the real part of the dielectric constant and loss parameters, eventually indicating the presence of higher frequency resonances, or the onset of Rayleigh scattering. This increasing losses at higher frequencies are particularly noteworthy in comparison to the high-resistivity crystalline silicon data shown in Fig. 7, which excels with respect to losses, especially at higher frequencies. One should note that the silicon loss values measured here ($\alpha \approx 0,05$ cm^{-1}, increasing toward lower energies up to $\alpha \approx 0,3$ cm^{-1}) agree with the ones given in [15], but are significantly higher than the low-frequency values reported in [16]. One should also take notice that the oscillatory modulation on the data derived for the alumina sample depicted in Fig. 3 is an experimental artefact due to the thin sample thickness, which prevents a precise separation of different Fabry–Perot reflection orders. The oscillations are, however, on the order of the standard deviation of the measurements.

IV. Conclusions

An analysis of low-cost high-dielectric constant materials has been presented. All materials that were tested exhibited low losses, with loss-tangent values $(\tan\delta)$ typically in the order of 0.02 with a tendency toward higher losses up to 0.06 at higher frequencies. Alumina stands out in comparison to the other low-cost dielectric materials with respect to losses, exhibiting a continuously low-loss tangent $<$0.02 up to 3 THz, followed closely by the zirconium–tin–titanate sample with a dielectric constant of 37. The presented materials offer a wide range of real parts of the dielectric constants (ε) on the order of 6.5, 9.3, 16, 37, and 93 for the respective materials and, therefore, can provide solutions to numerous engineering requirements. All materials are low cost and processable in order to enable the development of cost effective photonic crystal components in the terahertz spectral range.

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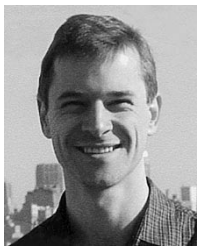

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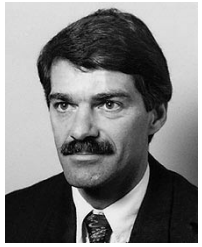

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