Invited Paper

On the dielectric properties of substrates with different surface conditions for submillimeter-wave and terahertz applications

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Abstract: Dielectric constant and loss tangent are essential material parameters in designing and predicting the performance of submillimeter-wave and terahertz devices. In this paper we investigate dielectric properties of substrate materials using pulsed time-domain spectroscopy. It is found that these dielectric properties depend on the preparation process of the sample under test as different process results in different surface condition. Two different substrates, namely, printed-circuit board laminate and 3D printing polymer, with different preparation methods are used to illustrate the impact of surface condition of the sample to the extracted dielectric properties. A Fresnel zone-plate lens with a circular grating reflecting plane operating at 0.3 *THz* is designed and measured. Good agreement between simulation and measurement results is achieved when proper dielectric properties and surface model are employed.

Keywords: Terahertz time-domain spectroscopy (THz-TDS), Polymers, Refractive index, Absorption coefficient, Dielectric constants

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1. Introduction

Dielectric properties of printed-circuit board (PCB) laminates used in antenna designs and high-speed signal analyses are nominal values presented in datasheets provided by material vendors. However, the maximum operating frequencies available in the datasheets for these laminates are mostly limited to tens of GHz range only. If these laminates are used in submillimeter-wave (SMMW) and terahertz (THz) devices, prior information on dielectric constant and loss tangent of each laminate are essential for successful designs. There are many techniques to measure these values. Methods like parallel plates, transmission line, resonant cavity and free space [1] are common in microwave band measurements. For capturing the material properties at SMMW and THz bands, transmission time-domain THz spectroscopy [2-4] has been a popular approach in the last decade. The pulsed THz-time domain spectrometer (THz-TDS) is a high precision equipment to capture both the amplitude and phase of the signals transmitted through the sample-under-test by calculating the difference between two coherent THz beam signals. With this spectrometer, conventional PCB laminates and various kinds of polymers or new-form of synthetic materials for 3D printing can be characterized and the retrieved dielectric properties be incorporated in the design of THz devices [5]. Fig. 1 shows the schematic diagram of a typical TDS system. The THz signal passes through the sample for measuring the transmission. From the measured transmission data, dielectric constant and loss tangent can be obtained. Unfortunately, in most published dielectric properties, no information was provided on how the sample-under-test was prepared. At SMMW and THz bands, surface condition of the sample would affect the transmitted field through the sample and therefore, the retrieved dielectric properties.

In this paper, we discuss the effect of surface condition of the testing samples which is different for different preparation process. The thickness of the sample can also affect the measured results. Both standard PCB laminate and 3D printing material are investigated. For PCB laminates, we remove the copper cladding using both chemical etching and laser removal approaches and they yield different results. Similarly, 3D printing materials with "Matte" and "Glossy" finishes also lead to different retrieved material properties. Based on the retrieved dielectric properties, we have designed a Fresnel zone-plate lens antennas operating at 0.3 *THz*. A circular grating is added to the reflecting ground to enhance the antenna gain. A laser fast prototyping process is employed to remove part of the copper to form the circular grating. With the use of corresponding dielectric properties and proper modeling of the burning marks caused by the laser prototyping, good agreement between the measured and simulated antenna gains is achieved.

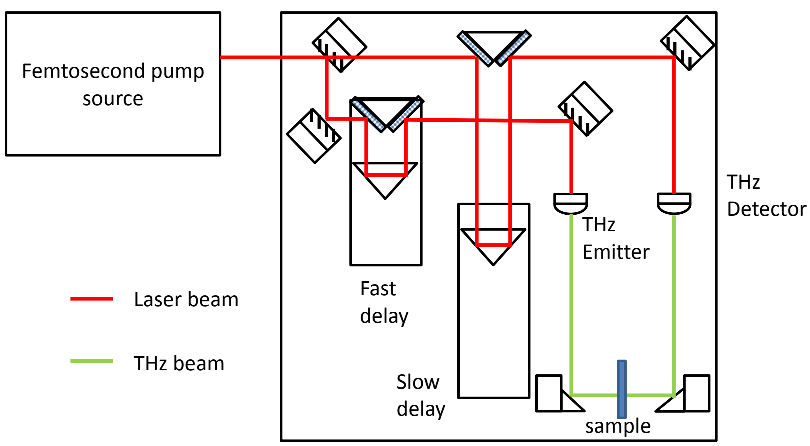

Fig. 1 TDS system operating in transmission mode.

2. Fabrication of testing samples

In order to show the effects of the surface condition of the testing samples on the measured dielectric properties, two substrates are chosen for the measurement. Each substrate is prepared with two processing techniques that are commercially available. Firstly, conventional high frequency PCB laminates, namely, Roger RT/Duroid® 5880, are prepared by chemical etching and laser copper cladding removal, respectively. Secondly, 3D printed samples are prepared by two different printing modes, namely, "Matte" and "Glossy" available in typical 3D printers. The two modes employ the same file describing the 3D object and Objet30 from Stratasys ™ Ltd is employed for printing the samples. The polymer material is VeroBlue RGD240 which will be hardened when exposed to ultra-violet light.

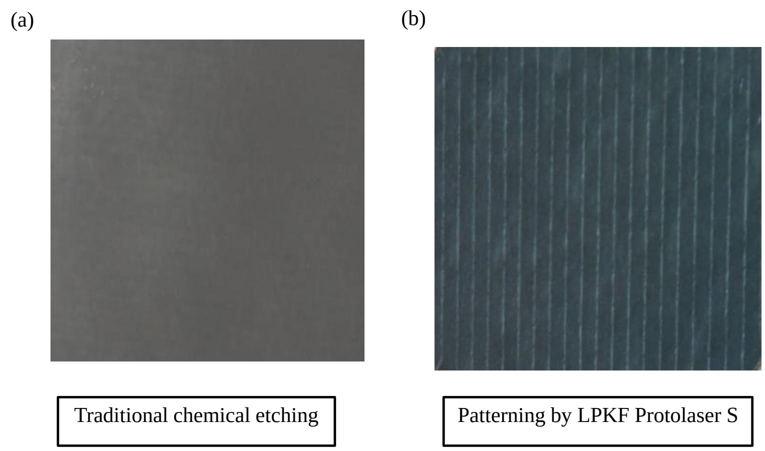

Fig. 2 Photos of RT 5880 substrate with copper cladding removed with 4 time magnification under microscope. (a) Removal by conventional chemical etching. (b) Removal by laser.

A. Roger RT/Duroid® 5880 samples

Two identical standardized RT5880 PCB substrates are processed to remove the copper cladding in house. The substrate is 0.254 *mm* thick, 20 *mm* × 20 *mm* in size and has a 9 μm thick copper cladding on both sides. The substrate material is a PTFE (Polytetrafluoroethylene) composite. Fig. 2 shows the RT 5880 substrates with copper cladding removed. In Fig. 2a, the RT5880 is etched by hydrogen peroxide [10%] (H_2O_2) with hydrochloric acid [30%] (HCl). The condition of the etched surface is quite smooth and the original color of the substrate is maintained. In contrast, on the substrate surface with copper cladding removed by laser, there are burning marks as shown in Fig. 2b. They are quite profound when viewed under a microscope. Our in-house LPKF laser PCB patterning machine employs a laser to pattern the PCB. For large area of copper cladding removal, the laser runs in raster path for that area to burn the copper into strips which peel off from the substrate surface and then vacuumed away. Both samples are visually-checked to confirm that no copper traces remain on the substrate. The two samples are then measured by the THz TDS to have material property retrieval.

B. 3D printed material samples

The samples are printed by the Stratasys™ Objet 30 3D printer with its highest resolution output. The printing liquid polymer can transform into the rigid opaque material in solid form. This printing polymer is photo-sensitive which can be solidified by exposing to ultra-violet rays. In Fig. 3, the printouts of two 3D dielectric samples are shown. We can observe that the surface of the printed sample is quite rough in Fig. 3a. It is because the printing mode is calibrated to "Matte". The printing line marks can be observed visually. In Fig. 3b, the surface of sample is smooth. The printing mode is calibrated to "Glossy". "Matte" can produce the highest accuracy in printing dimension according to the input 3D structural file. "Glossy" can provide good finishing but incur 3% of printing error as indicated in the printer user manual. All testing substrates are printed 20 *mm* × 20 *mm* in size but with different thicknesses. The thicknesses are 0.5, 1, 2 and 4 *mm*. Two different surface roughness modes (smooth/rough) are chosen for each thickness value. Totally, there are 8 samples for material property retrieval.

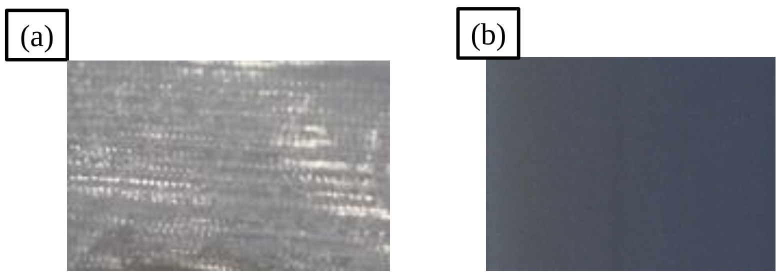

Fig. 3 Photos of printed 3D printout by different printing modes in 4 time magnification under microscope. (a) "Matte" finish. (b) "Glossy" finish.

3. Material properties retrieval

An EKSPLA THz time-domain spectrometer T-SPEC series is employed for material property retrieval. Samples will be placed at the location shown in Fig. 1. Measured time-domain waveforms, spectrum waveforms and data of absorbance are all used to calculate the reflective index, power absorption coefficient, dielectric constant and loss tangent of each sample.

In Fig. 4, photo of the sample inside the THz TDS for transmission test is shown. Since the THz ray cannot be visually detected. A virtual dashed line colored in green is added in Fig. 4 for illustration. The beam spot hit on the sample-under-test is around 1 mm^2 in circular shape. It implies that the sample size is large enough to cover the detection area. In Fig. 5, the screen capture of time-domain waveform of the TDS measurement platform for RT 5880 is shown. The red colored line is the pre-measured reference curve. Actually, it is the response of the atmospheric data inside the TDS before the placement of sample-under-test. The green colored curves are the RT 5880 measured data. In Fig. 5a, the RT 5880 is etched by conventional chemical method. In Fig. 5b, the copper is removed by laser machining. In comparison, the red curve for laser etching method causes a higher loss and lower magnitude in transmitted waveform. The detailed calculated results are shown in Section 4.

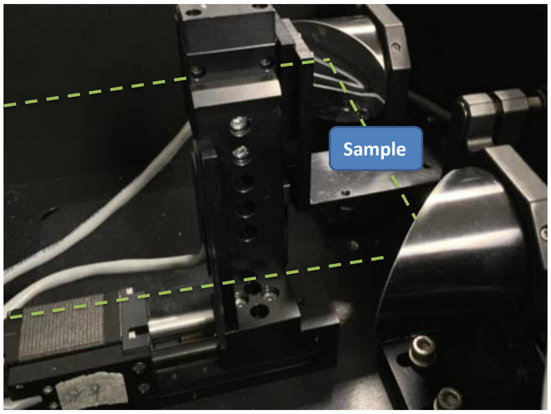

Fig. 4 Photo of the sample-under-test inisde the TDS setup for transmission test. The sample is fixed on a motorized stage for accurate alignment.

(a)

(b)

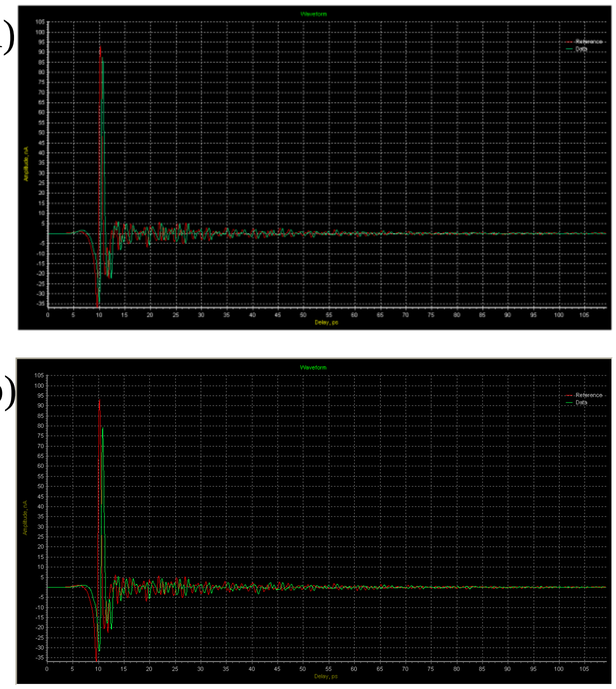

Fig. 5 Screen capture of RT5880 samples for time-domain waveforms. (a) Chemically-etched sample. (b) Laser-ablated sample.

4. Calculations of the complex refractive index, power absorption coefficient, loss tangent and the dielectric constant

Time-domain waveforms are captured for both RT5880 PCB substrate and 3D printed material –VeroBlue RGD240 with smooth and rough surfaces. Based on the measurement, material properties are calculated using FFT data of the measured waveforms following the procedure detailed in [6]. The calculated maximum frequency is up to 3.0 *THz*.

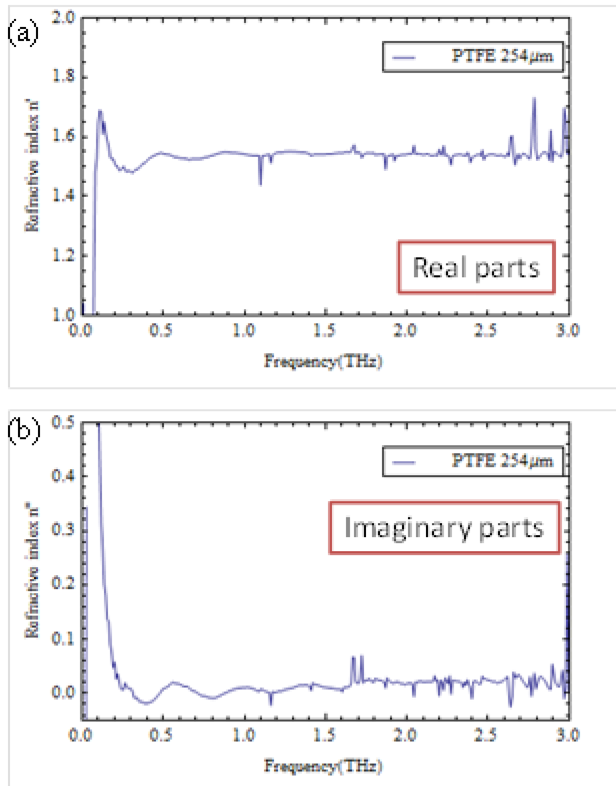

Fig. 6 Calculated complex refractive indices of chemically-etched RT5880 PCB substrate. (a) Real part. (b) Imaginary part.

A. Roger RT/Duroid® 5880 samples

Fig. 6 shows the calculated real and imaginary parts of reflective index of the RT5880 PCB substrate by chemical etching method. The real part is stable from 1.48 to 1.55 across the lower frequency band. Similarly, we can observe variation for the imaginary part from 0.05 to 0.7. However, comparing Fig. 6 and Fig. 7, there is a significant difference for the frequency range between 0.2 to 1.2 *THz*. Fig. 7 shows the calculated real and imaginary parts of reflective index of the RT5880 substrate treated by laser ablation. There is a series of ripple appearing in both real and imaginary parts of the reflective index. This may be attributed to the laser marks on the substrate. Although the laser burning mark is 0.025 *mm* in width, the separation between two laser marks is 0.167 *mm*. It implies that these laser marks are periodically distributed on the substrate in sub-wavelength dimension of 0.5 *THz*. There is a sub-wavelength effect which may reflect the incoming signal for this range of frequencies. In Fig. 8, the calculated power absorption coefficients are shown. Comparing the absorption rate between Fig. 8a and 8b, laser-ablated method indeed reaches higher values across the lower frequency range.

Consequently, the overall loss tangent values for the RT5880 with laser burning marks are higher than the one prepared by chemical etching. The detailed values can be found in Fig. 9. Taking 0.5 *THz* as an example, the loss tangent of chemically-etched sample is 0.025. The loss tangent for the laser-ablated sample can reach up to 0.078 that is almost three times higher in value. Figs. 10 and 11 are the calculated complex dielectric constants with real and imaginary parts for both chemically and laser-ablated samples, respectively.

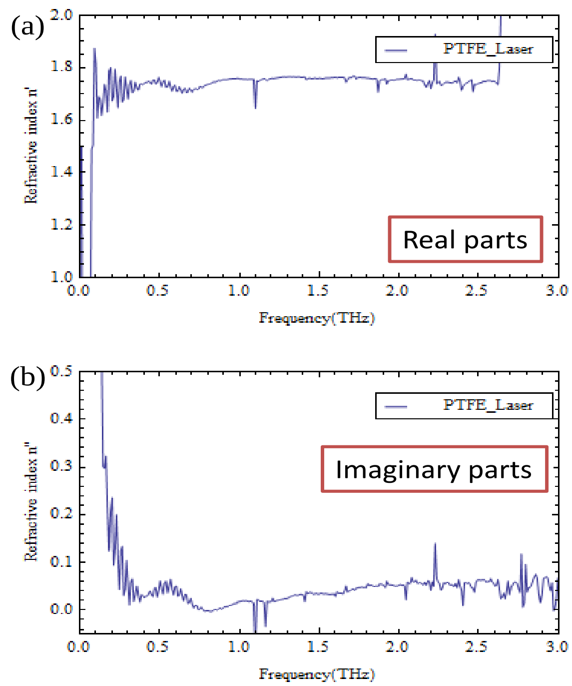

Fig. 7 Calculated complex refractive indices of laser-ablated RT5880 PCB substrate. (a) Real part (b) Imaginary part.

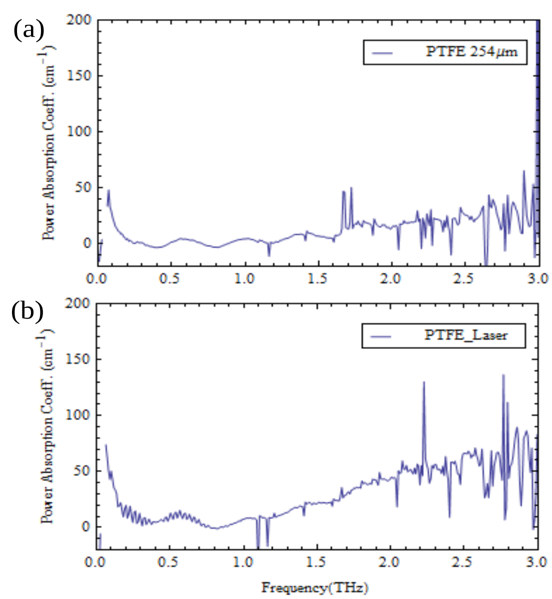

Fig. 8 Calculated power absorption coefficient (per cm^{-1}) of RT5880 substrate. (a) The chemically-etched sample. (b) The laser-ablated sample.

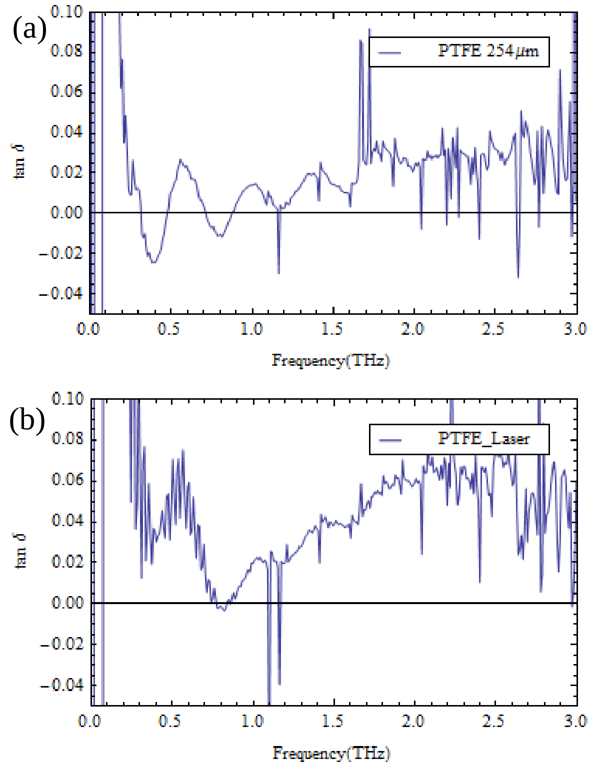

Fig. 9 Calculated loss-tangent values of RT5880 substrate. (a) Chemically-etched sample. (b) Laser-ablated sample.

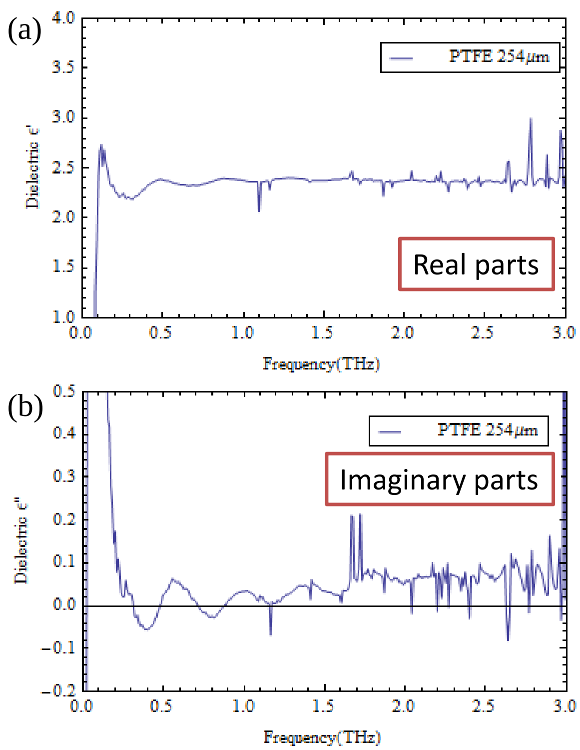

Fig. 10 Calculated complex dielectric constant of chemically-etched RT5880 PCB substrate. (a) Real part. (b) Imaginary part.

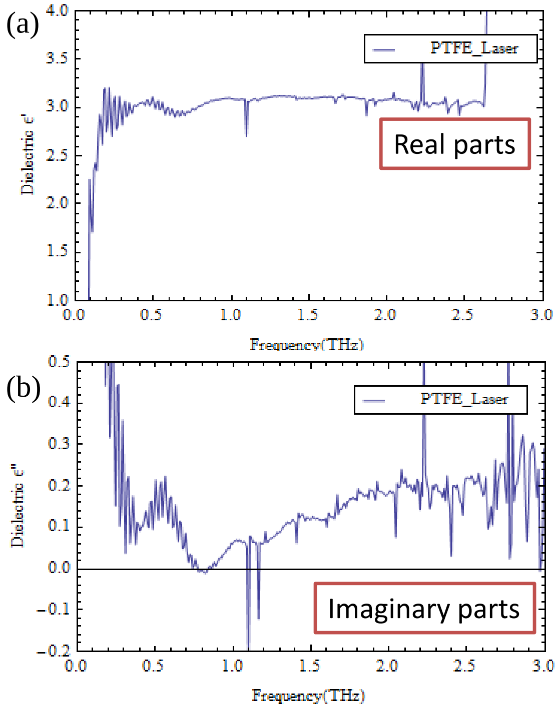

Fig. 11 Calculated complex dielectric constant of laser-ablated RT5880 PCB substrate. (a) Real part. (b) Imaginary part.

B. 3D printed material - VeroBlue RGD240

Figs. 12 and 13 show the calculated complex reflective indices of the photosensitive polymer with rough surface “r” and smooth surface “s” respectively. Both of the figures here are tested with different thicknesses: 0.5, 1, 2, and 4 *mm*. Comparing the responses lower than 1 *THz* for Figs. 12a and 13a, surface roughness of this printed material does not have adverse effect to the measurement. However, when the thickness of the sample is reduced to 0.5 *mm*, more profound ripples can be observed. However, when the thickness of the sample increases, the magnitude of the ripples reduces. When the thickness reaches 4 *mm*, the response drops rapidly which indicated that the signal strength is very weak. Low signal-to-noise ratio affects the calculation. In Fig. 14, the calculated power absorption coefficients are shown. The absorption losses across the band are similar for both smooth and rough surfaces. In Fig. 15, for the thickness in 0.5, 1, 2 *mm*, the calculated real part of dielectric constant varies from 2.75 to 2.9 for frequencies lower than 1 *THz*. The value is quite stable across this frequency band. However, for the 4 *mm* thick samples, the received signal transmitting through the sample is too low to be detected accurately due to the weak output power of the THz ray. All the subsequent results calculated are incorrect. Shown in Fig. 16 is the calculated loss tangent of VeroBlue RGD240 substrate.

5. Case study: importance of using correct dielectric constant and loss tangent in simulation

A Fresnel zone plate lens (FZPL) antenna operating at 0.3 *THz* with a novel feeding structure is designed and fabricated [7] using RT5880 substrate. During the design stage, the dielectric constant and loss tangent are chosen as 2.3 and 0.025 for both lens and feeding layers, respectively, as shown in Figs. 9a and 10a. The geometry of the proposed antenna is shown in Fig. 17. The antenna consists of two main components: FZP lens layer and feeding layer. Laser ablation method is used to produce high precision patterning on both layers. Unfortunately, there are burning marks left on the substrate surface that can be visually identified as shown in Figs. 18b and 19a. Based on these fabricated substrates, we re-simulated the antenna with burning marks as well as the corresponding dielectric constant (3.1) and loss tangent (0.078) as shown in Figs. 9b and 11a. In Fig. 19a, the photo of FZP lens is captured and the laser burning marks are shown. In Fig. 19b, the burning marks are added in the Ansys™ HFSS [8] simulation with the same dimensions on both sides of the lens. In addition, laser burning marks are also modelled for the top surface of the feeding layer. For the simulated and measured antenna gains shown in Fig. 20, there is a significant difference between the original simulated and measured results. After modeling the laser burning marks in the simulation and comparing to the measured results, it is concluded that the gratings on the substrate definitely affects the effective dielectric constant and loss tangent of the fabricated substrate. Referring to Fig. 20, the measured results are in good agreement with the simulated gains of FZPL antenna with laser burning marks properly modelled.

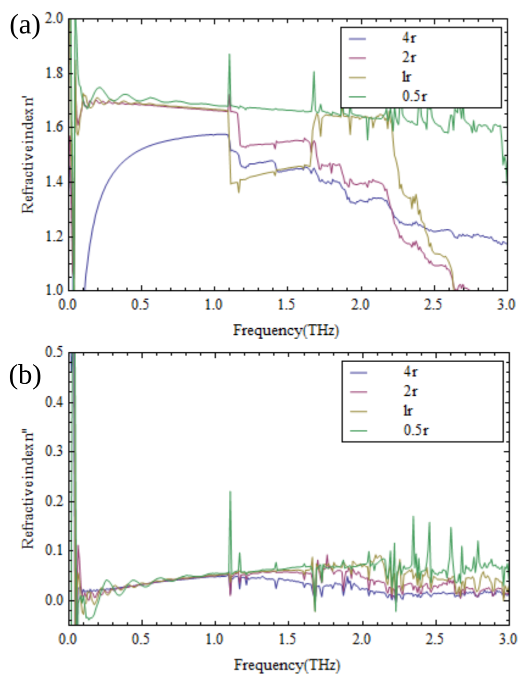

Fig. 12 Calculated complex reflective indices of rough surface VeroBlue RGD240 substrate in different thickness. (a) Real part. (b) Imaginary part.

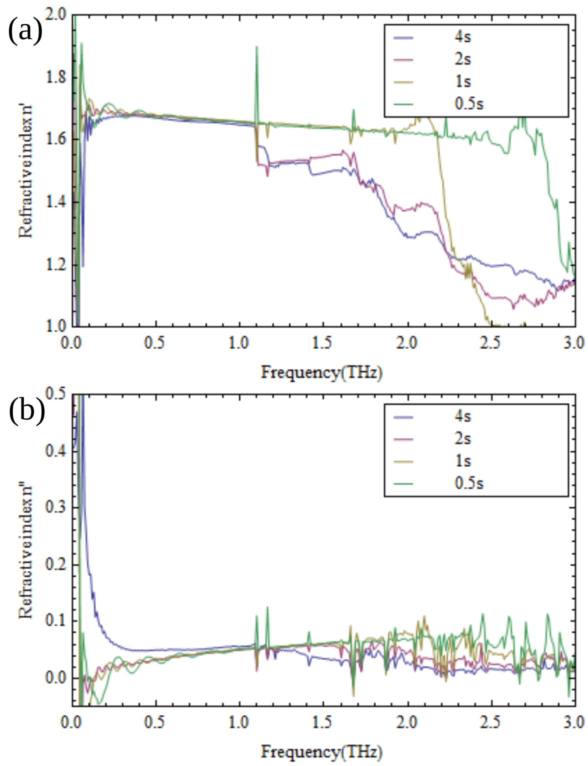

Fig. 13 Calculated complex reflective indices of smooth surface VeroBlue RGD240 substrate in different thickness. (a) Real part. (b) Imaginary part.

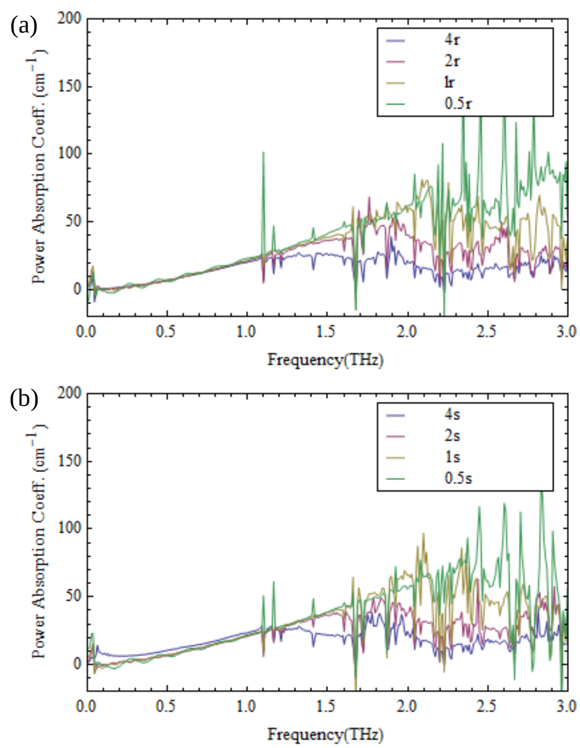

Fig. 14 Calculated power absorption coefficient of VeroBlue RGD240 substrate in different thickness. (a) Rough surface. (b) Smooth surface.

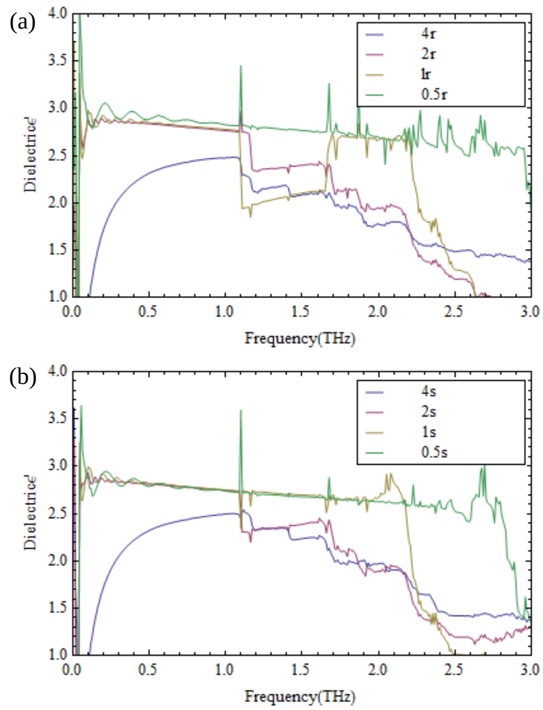

Fig. 15 Calculated real part of dielectric constant of VeroBlue RGD240 substrate in different thickness. (a) Rough surface. (b) Smooth surface.

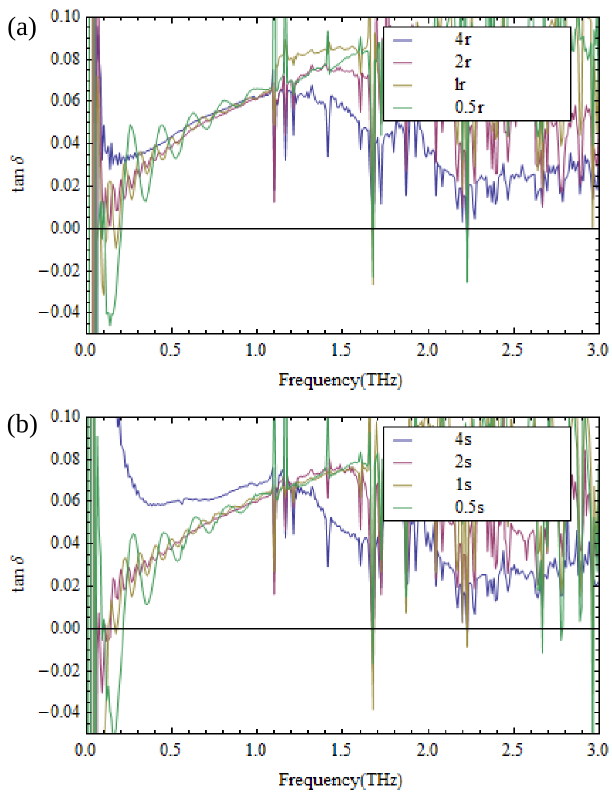

Fig. 16 Calculated loss tangent values of VeroBlue RGD240 substrate in different thickness. (a) Rough surface. (b) Smooth surface.

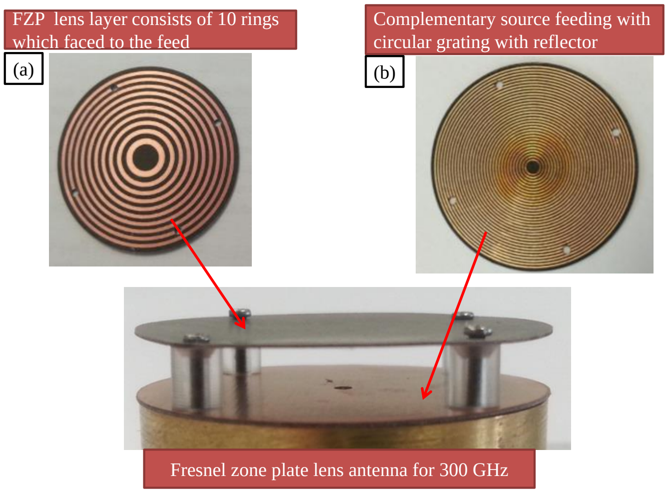

Fig. 17 Geometry of Fresnel zone plate lens antenna. (a) FZP lens layer. (b) Feeding layer with circular gratings on the reflector.

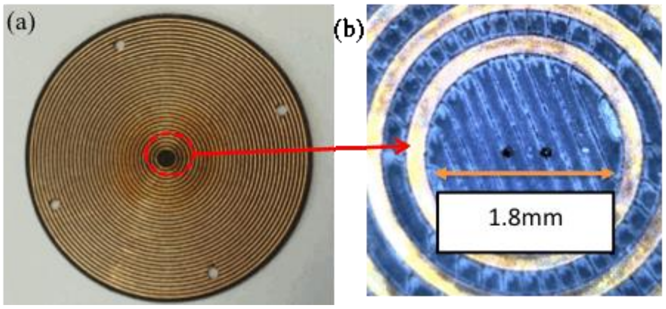

Fig. 18 Antenna prototype fabricated by laser ablation method. (a) Feeding structure using RT5880 substrate. (b) Magnified view of the feeding structure with burning marks.

6. Conclusion

Material properties retrieval for terahertz band application is a necessity before any design. However, the surface condition varies with fabrication process that is often overlooked. It is very important to characterize dielectric constant and loss tangent directly from the true fabricated samples rather than published data when designing SMMW and THz devices. To illustrate our points, we have studied the dielectric properties of two different substrate materials each prepared with two different fabrication processes. The retrieved dielectric properties using transmission THz-TDS are different for different surface conditions. Good agreement in simulated and measured gains of the FZP lens antenna is obtained with proper dielectric properties are retrieved and correct surface model are employed.

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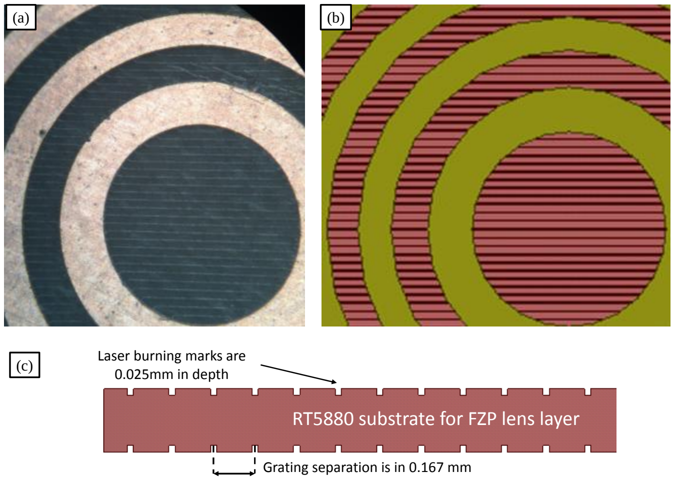

Fig. 19 Modifications in the HFSS simulation by adding laser burning marks. (a) Photo of FZP lens with burning marks on substrate. (b) Laser burning marks are added in simulation. (c) Cross-sectional view of FZP lens layer that fabricated on RT5880 substrate. The burning marks are in 0.025 *mm* in width and depth and they are separated by 0.167 *mm*.

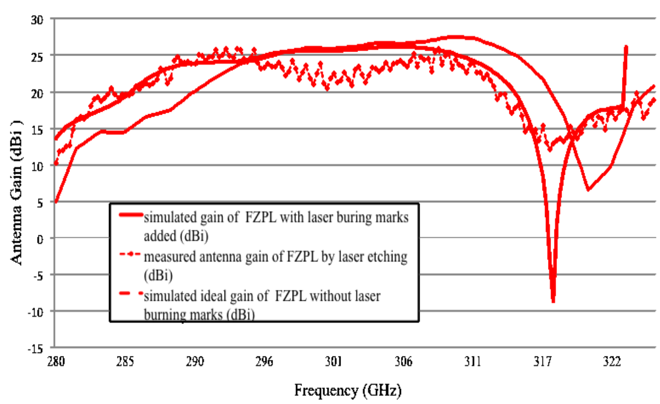

Fig. 20 Simulated and measured results of antenna gain with and without laser burning marks.

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