A Simple Experimental Method to Analyze the Properties of Terahertz-wave Propagation in Complex Atmosphere

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Abstract— In this paper, a much simple experimental method is proposed to analyze the terahertz-wave propagation properties. The schematic diagram and process of parameters retrieval are presented in detail. Two terahertz-wave transmission paths are presented in one vacuum chamber but with different lengths. Two switches are required to select different transmission paths in a short time by which the system errors such as assembling error and instrumental error can be ignored. Different complex atmosphere can be injected into the vacuum chamber and its equivalent electromagnetic parameters such as propagation constant can be retrieved. Then the detailed propagation properties can be further calculated. The above method is certificated in full-wave simulation and the error is no more than 0.33% when isotropic material is used to simulate the atmosphere.

1. INTRODUCTION

Terahertz-wave has received considerable attention in both scientific and engineering communities for its higher communication speed, better imaging resolution and less harm medical care [1, 2]. More recently, satisfactory achievements are obtained in designing terahertz source and detector equipments [3, 4]. But the advancement of researches on terahertz-wave propagation properties is still poor. The main analysis method is given by ITU-R [5] which is only suitable for idea atmospheric as only the oxygen, nitrogen and water vapor are considerable. For real complex atmosphere, experimental method is preferred. However, the presented experimental systems are extremely complicated and expensive [6, 7]. They are difficult to be copied by common fabricated technology.

In this paper, a much simple experimental method is proposed to analyze the terahertz-wave propagation properties. Two terahertz-wave transmission paths are presented in one vacuum chamber but with different lengths. Two switches are required to select different transmission path in a short time by which the measurement errors such as assembling error and instrumental error can be ignored. Different complex atmosphere can be injected into the vacuum chamber and its equivalent electromagnetic parameters such as relative permittivity and permeability can be retrieved. The detailed retrieval process are listed and the method is certificated by full-wave simulation when isotropic material is used to simulate the atmosphere.

2. METHOD ANALYSIS

As for terahertz-wave propagation, the absolute results are easily affected by different kinds of errors, such as assembling error, instrumental error and environmental disturbance. Here, we suggest a comparison method to analyze the propagation properties of terahertz-waves. The schematic diagram are presented in Fig. 1, where two terahertz-wave transmission paths are presented in one closed vacuum chamber but with different lengths. Different complex atmosphere can be simulated in the closed chamber. Two switches are added to select different transmission path in a short time by which the measurement errors can be ignored. For path 1, the total scatter matrix $[S]_{P1}$ from port 1 to port 2 can be easily obtained by simulation or experiment. Then, the total transmission matrix $[T]_{P1}$ can be calculated by

$$[T]_{P1} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{P1} = \begin{bmatrix} (-S_{11}S_{22} + S_{12}S_{21})/S_{21} & S_{11}/S_{21} \\ -S_{22}/S_{21} & 1/S_{21} \end{bmatrix}_{P1} = [T]_{P1-L}[T]_{P1-R}, \tag{1}$$

where

$$[T]_{P1-L} = \begin{bmatrix} T_{L11} & T_{L12} \\ T_{L21} & T_{L22} \end{bmatrix}_{P1}, \quad [T]_{P1-R} = \begin{bmatrix} T_{R11} & T_{R12} \\ T_{R21} & T_{R22} \end{bmatrix}_{P1} = \begin{bmatrix} T_{L11} & -T_{L21} \\ -T_{L12} & T_{L22} \end{bmatrix}_{P1}. \tag{2}$$

For path 2, the total scatter matrix $[S]_{P2}$ from port 1 to port 2 can be also easily obtained by simulation or experiment. Then, the total transmission matrix $[T]_{P2}$ can be calculated by

$$[T]_{P2} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{P2} = \begin{bmatrix} (-S_{11}S_{22} + S_{12}S_{21})/S_{21} & S_{11}/S_{21} \\ -S_{22}/S_{21} & 1/S_{21} \end{bmatrix}_{P2} = [T]_{P2-L}[T]_{atm}[T]_{P2-R}, \quad (3)$$

where

$$[T]_{atm} = \begin{bmatrix} e^{\gamma\Delta l} & 0 \\ 0 & e^{-\gamma\Delta l} \end{bmatrix}. \quad (4)$$

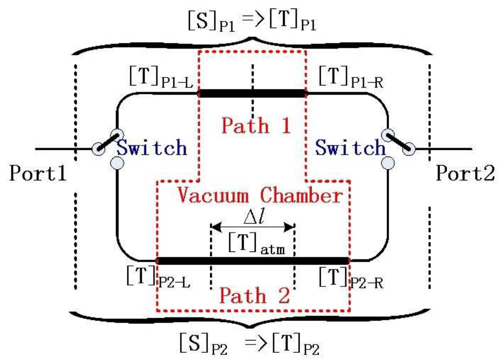


Figure 1: The schematic diagram of parameter retrieval.

Based on detailed optimization and design, $[T]_{P2-L} = [T]_{P1-L}$ and $[T]_{P2-R} = [T]_{P1-R}$ can be achieved. Then, the transmission matrix of complex atmosphere layer with propagation constant γ and length of l can be retrieved from Eqs. (1)–(3). For convenience, we assume that

$$[T]_{P1} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{P1} = \begin{bmatrix} a_1 & b_1 \\ c_1 & d_1 \end{bmatrix}, \quad [T]_{P2} = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}_{P2} = \begin{bmatrix} a_2 & b_2 \\ c_2 & d_2 \end{bmatrix}. \quad (5)$$

We further obtain

$$S_{21-atm} = e^{\gamma\Delta l} = \frac{2b_1b_2 + a_2d_1 + a_1d_2 - \sqrt{T_0}}{2(a_2d_2 + b_2^2)}, \quad (6)$$

$$\gamma = \alpha + j\beta = \ln(S_{21})/\Delta l, \quad (7)$$

where

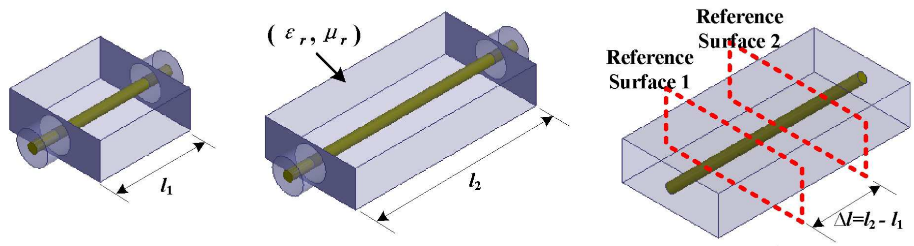
$$T_0 = 4b_1b_2a_2d_1 + 4b_1b_2a_1d_2 + a_2^2d_1^2 - 2a_2d_1a_1d_2 + a_1^2d_2^2 - 4a_2d_2b_1^2 - 4a_1d_1b_2^2. \quad (8)$$

Now, we summarize the retrieval process as follows:

(1) Switch on path 1 and obtain the total scatter matrix $[S]_{P1}$;
(2) Switch on path 2 and obtain the total scatter matrix $[S]_{P2}$;
(3) Calculate the $[T]_{P1}$ and $[T]_{P2}$ by Eqs. (1) and (3);
(4) Calculate the propagation constant γ by Eqs. (6)–(8);
(5) Calculate the propagation properties with different lengths by $S_{21-atm} = e^{\gamma l}$.

3. SIMULATION VERIFICATION

In this section, we would like to verify the proposed retrieval method using full-wave simulation software of HFSS. The simulation models are presented in Fig. 2, where Figs. 2(a) and (b) refer to two terahertz-wave transmission paths with the same input/output transitions but different lengths of l_1 and l_2. Fig. 2(c) refers to the continuous middle part which is used for the verification of our retrieval method. Two samples are detailed analyzed, where $l_1 = 1$ mm and $l_2 = 2$ mm are fixed. The isotropic material of $\varepsilon_r = 1 - j0.1$ and $\varepsilon_r = 3 - j0.45$ are filled in the chambers, respectively.



(a) (b) (c)

Figure 2: The simulation models. (a) Path 1. (b) Path 2. (c) Middle part.

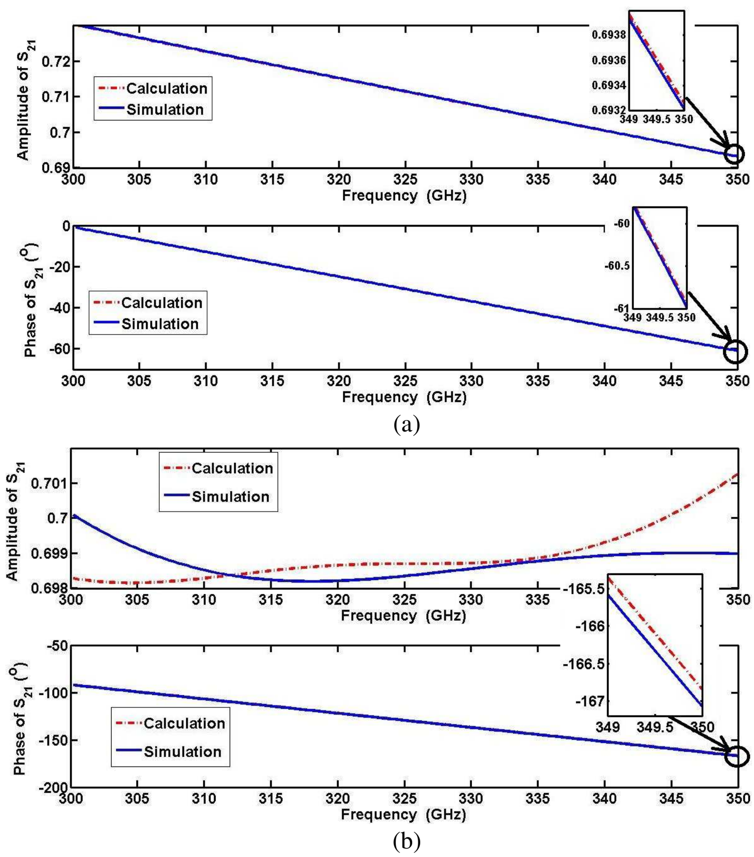


Figure 3: Retrieval results of two samples. (a) $\varepsilon_r = 1 - j0.1$, $\mu_r = 1$. (b) $\varepsilon_r = 3 - j0.45$, $\mu_r = 1$.

Relative amplitudes and phases of S_{21} retrieved by our proposed method are presented in Figs. 3(a) and (b), which are also compared to the simulated results by HFSS. From Fig. 3, we can see that the maximum relative errors of amplitude and phase are only 0.33% and 0.2%, respectively, which are presented at 350 GHz in sample 2. Compared Fig. 3(a) to Fig. 3(b), we further know if better matching through both paths are achieved, higher retrieval precision is hoped to be obtained.

We clarify that the coaxial waveguide is just used for input and output the signal in simulation. Other waveguide structures such as metallic rectangular waveguide or microstrip line should be replaced in real fabrication. What's more, the PEC-cylinder in closed rectangular chambers can also be replaced by two antennas with much larger chambers, by which better matching through both paths are easily finished.

4. CONCLUSION

We propose an experimental method to analyze the terahertz-wave propagation properties in this paper. A comparison method is suggested in the detailed retrieval process, by which the errors can be reduced greatly. Compared to those TDS (time-domain spectroscopy)-based experimental methods, our proposed method is much simpler and easier to be fabricated. Different propagation modes such as wire transmission by PEC cylinder or wireless radiation by antennas can be used in such an experimental system. The core technology is just to be sure the identical transition and high isolation of path 1 and 2.

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