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Chong Gao,1 En Li,1 Yang Zhou,2,a) and Yong Gao1,a)

AFFILIATIONS
1School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
2Chengdu University of Information Technology, Chengdu 610103, China

a)Authors to whom correspondence should be addressed: zhouyang@cuit.edu.cn and gy_wlee@163.com.

ABSTRACT

A thin film is often coated on the dielectric rods used in traveling wave tubes to provide microwave attenuation. The quality of the thin film will affect the performance of the traveling wave tube. To evaluate the quality of the thin-film by measuring the attenuation performance of the dielectric rod, modified parallel strips with a sample hole are designed to provide a relatively reasonable field working environment for the attenuation evaluation. After analyzing the field distribution of the parallel strips, a sample hole is designed on the side of parallel strips, which is tangent with the outer edge of the strip. An arcuate taper is introduced into the parallel strips to reduce the impedance mismatching. Finally, two unqualified and qualified dielectric rods are measured using the modified parallel strips at frequencies 12 GHz and 18 GHz. The measured results indicate that it is feasible to evaluate whether the thin-film coated on the dielectric rod is qualified or not.

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Thin-film processing is always an important research field for materials science.1–4 Measurement and evaluation of the thin-film under the real application environment will help the designers better apply the material. In the vacuum electron devices,5,6 such as traveling wave tubes (TWTs), the dielectric rod coated with carbon thin-film is a very important component for the device performance. A thin-film is coated along some parts of the dielectric rod with different thicknesses. In fact, the actual field in TWT is very complex, which is hard to seriously calculate or simulate. However, according to the Pierce model, a similar E-field of the helix in TWT can be described in Fig. 1. We can find that the E-field is approximately curved between different helixes. This field distribution inspired us to design a test fixture for the attenuation measurement of the dielectric rod.

To evaluate the attenuation of the thin-film on the dielectric rod, several methods have been investigated. The double ridge waveguide and the height reduced rectangular waveguide with a sample hole in the center can be used to measure the attenuation distribution. For both test fixtures,8–10 the E-field direction goes straightly from up to down, and this is different from the real E-field direction in TWT. Another novel test fixture11 is designed to measure the attenuation distribution with higher measurement resolution, but the E-field of the parallel strips is also different. A simple method to evaluate the attenuation of the carbon thin-film is to directly put the dielectric rod into an actual TWT. However, it is a high-cost and not applicable measurement process. A rough but common method is to measure the resistance distribution of the thin-film by using a resistivity tester for the indirect evaluation. Other methods such as simulation calculation and rigorous field analysis find it very difficult to evaluate the real performance of the thin-film.

In this paper, we concentrate on the attenuation evaluation of the dielectric rod to determine the quality of the thin-film. A modified parallel strip fixture is introduced to provide a relatively reasonable field working environment for the attenuation measurement. This is explained by analyzing the parallel strips. Meanwhile, an arcuate taper on the opposite of the sample hole is designed to reduce the impedance mismatching caused by the hole. Finally, two
unqualified and qualified dielectric rods are measured by using the modified parallel strips at different frequencies. Compared to the other methods mentioned in the preceding paragraph, as shown in Table I, the proposed method has an advantage in the evaluation of dielectric rod.

The parallel strips are constructed by a nonair or air dielectric substrate and two conduct strips. In fact, as for the condition of the nonair dielectric, a pure TEM does not exist. If air or other nonair dielectrics inside and outside of the strips are the same, the propagation mode of parallel strips will be a pure TEM. However, the presence of the dielectric-air interface turns a pure TEM in parallel strips with only one dielectric into a quasi-TEM hybrid mode. This makes the analysis of the fields or propagation parameters of the parallel strips complex. For the quasi-TEM mode, there are hybrid TE and TM modes propagating in parallel strips, which are caused by the frequency-dependent current distribution on strips.

As shown in Fig. 2, since the parallel strips are a balanced transmission line, the voltages on the bottom and top strips are opposite. An infinite fictitious GND (ground) is supposed to exist at the middle of two strips, and the parallel strips can be regarded as two back-to-back microstrips (upper microstrip is above the virtual ground plane, and lower microstrip is under the virtual ground plane). The field above the fictitious GND is assumed to be similar to the sin-plane, and lower microstrip is under the virtual ground plane (middle of two strips, and the parallel strips can be regarded as two back-to-back microstrips).

An infinite fictitious GND (ground) is supposed to exist at the middle line, the voltages on the bottom and top strips are opposite.

As shown in Fig. 2, since the parallel strips are a balanced transmission line, the voltages on the bottom and top strips are opposite. An infinite fictitious GND (ground) is supposed to exist at the middle of two strips, and the parallel strips can be regarded as two back-to-back microstrips (upper microstrip is above the virtual ground plane, and lower microstrip is under the virtual ground plane). The field above the fictitious GND is assumed to be similar to the single microstrip. As mentioned in the above paragraph, the current distributed on strips causes the quasi-TEM mode and should be analyzed to obtain the fields in the microstrip field by using Fourier transform in Ref. 12. The forthcoming analysis is limited to the upper or lower microstrip, and the whole field of the parallel strips can be obtained by the mirror theory. The surface current on the strip has vector components both in the x and z directions, namely, $I_{x}(x)$ and $I_{z}(x)$, as shown in Fig. 3. According to Eqs. (1) and (2), the normalized $I_{x}(x)$ and $I_{z}(x)$ can be described in Figs. 3(c) and 3(d). Actually, $I_{x}(x)$ is far less than $I_{z}(x)$ so that the x-direction current component $I_{x}(x)$ can be ignored.

$$I_{x}(x) = \begin{cases} I_{0} \sin \frac{x}{w}, & |x| \leq 0.4w, \\ I_{0} \sin \frac{x}{w} \cos \frac{\pi}{2w}, & 0.4w \leq |x| \leq 0.5w, \\ 0, & |x| > 0.5w. \end{cases}$$

The dielectric-air interface is a key inducement factor for the appearance of the current component $I_{x}(x)$. However, based on the fact that the amplitude of $I_{x}(x)$ is much smaller than the amplitude of the $I_{z}(x)$, the TEM mode is assumed existing in parallel strips. The expressions of all field components can be written as

$$\begin{align*}
E_{xi} &= \frac{\partial \psi_{hi}}{\partial x} - \frac{\omega}{k} \frac{\partial \psi_{hi}}{\partial y}, \\
E_{yi} &= -\frac{\partial \psi_{hi}}{\partial y} + \frac{\omega}{k} \frac{\partial \psi_{hi}}{\partial x}, \\
E_{zi} &= \frac{\omega^{2} \mu_{0} \epsilon_{0} \epsilon_{r}}{j k \psi_{hi}}, \\
H_{xi} &= \frac{\omega \epsilon_{0} \mu_{0} \epsilon_{r}}{k} \frac{\partial \psi_{hi}}{\partial y} - \frac{\partial \psi_{hi}}{\partial x}, \\
H_{yi} &= \frac{\omega \epsilon_{0} \mu_{0} \epsilon_{r}}{k} \frac{\partial \psi_{hi}}{\partial x} - \frac{\partial \psi_{hi}}{\partial y}, \\
H_{zi} &= \frac{\omega^{2} \mu_{0} \epsilon_{0} \mu_{r}}{j k} \psi_{hi},
\end{align*}$$

where $i = 1$ or 2 (for the dielectric region and air region, respectively), $\psi_{x}$ and $\psi_{z}$ are the scalar wave functions of the $E$ field and $H$ field with respect to $x$ and $y$, $\omega$ is the angular frequency, and $P$ is determined.
by the above quantities. The boundary conditions at the interface between the substrate and the air are presented as

\[
\begin{align*}
E_{x1} &= E_{x2}, \\
E_{z1} &= E_{z2}, \\
H_{x1} - H_{x2} &= I_z(x), \\
H_{z1} - H_{z2} &= -I_x(x).
\end{align*}
\]

(4)

According to Eqs. (3)–(5), we can get the solution matrix of the coefficients \(A, B, C,\) and \(D\). It should be noted that the four coefficients are dependently related to the Fourier transform variable \(X\),

\[
[S] = \begin{bmatrix}
0 & 0 & -I_x(X) & I_z(X)
\end{bmatrix},
\]

(6)

where

\[
[S] = \begin{bmatrix}
P_1 \sin \beta_1 d & -P_2 \sin \beta_2 d & 0 & 0 \\
-jX \sin \beta_1 d & -jX \sin \beta_2 d & \frac{\omega}{k} \cos \beta_1 d & \frac{\omega}{k} \cos \beta_2 d \\
0 & 0 & \frac{\omega}{k} \cos \beta_1 d & \frac{\omega}{k} \cos \beta_2 d \\
\frac{\omega}{k} \cos \beta_1 d & -jX \cos \beta_2 d & \frac{\omega}{k} \cos \beta_1 d & \frac{\omega}{k} \cos \beta_2 d
\end{bmatrix}.
\]

(7)

According to Eqs. (3)–(5), we can get the solution matrix of the coefficients \(A, B, C,\) and \(D\). It should be noted that the four coefficients are dependently related to the Fourier transform variable \(X\),

\[
[S] = \begin{bmatrix}
0 & 0 & -I_x(X) & I_z(X)
\end{bmatrix},
\]

(6)

where

\[
[S] = \begin{bmatrix}
P_1 \sin \beta_1 d & -P_2 \sin \beta_2 d & 0 & 0 \\
-jX \sin \beta_1 d & -jX \sin \beta_2 d & \frac{\omega}{k} \cos \beta_1 d & \frac{\omega}{k} \cos \beta_2 d \\
0 & 0 & \frac{\omega}{k} \cos \beta_1 d & \frac{\omega}{k} \cos \beta_2 d \\
\frac{\omega}{k} \cos \beta_1 d & -jX \cos \beta_2 d & \frac{\omega}{k} \cos \beta_1 d & \frac{\omega}{k} \cos \beta_2 d
\end{bmatrix}.
\]

(7)

Then, taking the inverse Fourier transform of \(\varphi_e(X, y)\) and \(\varphi_h(X, y)\) and substituting these into Eq. (3), we can get the E fields of the parallel strips.

\[
\varphi_{e1} = A \sin(\beta_1 y) \cos(Xx), \\
\varphi_{e2} = B e^{-\beta_1(y-d)} \cos(Xx), \\
\varphi_{h1} = C \cos(\beta_1 y) \sin(Xx), \\
\varphi_{h2} = D e^{-\beta_1(y-d)} \sin(Xx).
\]

(5)
In the upper microstrip, there are not any field components below the fictitious GND. According to the mirror image theory, the imaged surface currents ($I_m^x$ and $I_m^z$) must be inverse. Then, a similar analysis process can be conducted to determine the lower fields. Finally, the analyzed E-field is shown in Fig. 4. We can find that the E-field at the fringe of the parallel strips is similar to the real E-field distribution in TWT. Therefore, the parallel strips provide an electric field distribution which is similar to the actual application of the dielectric rod. This is very beneficial to the attenuation evaluation of the dielectric rod.

Based on the above analysis, a sample hole is set on the side of parallel strips, which is tangent with the outer edge of the strip. In the capacitance model of the parallel strips in Fig. 5, the characteristic impedance can be expressed as

$$Z_0 = \frac{v_0}{\sqrt{C_a C_d}},$$  \hspace{1cm} (8)

where $v_0$ is the phase velocity in vacuum, and $C_d = C_p + C_{f1} + C_{f2}$ and $C_a$ are the capacitances per unit length of the parallel strips with a dielectric substrate and an air dielectric, respectively. When the sample hole is introduced, $C_{f1} \neq C_{f2}$.

The unit capacitance along the length direction is written as

$$\Delta C = \frac{\varepsilon_0 \varepsilon_r w \Delta l}{4 \pi k d},$$  \hspace{1cm} (9)

where $\varepsilon_0$ is the vacuum permittivity, $\varepsilon_r$ is the relative permittivity, $\Delta l$ is the unit length of the parallel strips, $k$ is the electrostatic force constant, and $d$ is the distance between two strips. From Eq. (9), we can know that the unit capacitance must decrease linearly with the decrease in $w$ or $\varepsilon_r$. The appearance of the sample hole results in a decrease in $C_{f1}$. According to Eq. (8), an unavoidable impedance mismatching caused by the change of $C_{f1}$ in normal parallel strips should be considered. Therefore, in order to keep the consistency of characteristic impedance, the same arcuate tapers on the width of the top and bottom strips are designed to reduce the mismatching caused by the hole, as shown in Fig. 6. Length of the arcuate taper is equal to diameter ($2 \times Rh$) of the hole. Meanwhile, $w_s$ is simulated in HFSS to find an optimal value. By simulating different substrates with different permittivities, we can find that the effect of the sample hole will increase as the permittivity increases. Hence, the arcuate taper is more necessary for a high permittivity substrate. To achieve impedance transform from parallel strips to SMA (Small A Type) connectors, a similar structure is designed. Finally, the parallel strip fixture is printed on Rogers 5880 with a thickness of...
thin-film. To evaluate the qualification of the dielectric rods coated with a carbon thin-film, a fixture is designed and fabricated. The simulated and measured results of this fixture are shown in Fig. 8, and these results indicate that the fixture can work at a broadband frequency range from 1 GHz to 40 GHz. There is a sudden reduction at about 14 GHz in the measured S21. It may be caused by the error of fabrication and assembling.

A boron nitride (BN) dielectric rod coated with a carbon thin-film is measured by using the proposed fixture. The dielectric rod is inserted into the sample hole and passed through the fixture every 0.5 mm by using a moving device. Scattering parameters at different positions of the dielectric rod are obtained from the Vector Network Analyzer (VNA). Substituting S11 and S21 into the calculation expression in Refs. 19 and 20, we can get the attenuation distribution along the dielectric rod. Since the dielectric rod is applied at 12 GHz–18 GHz, one qualified and one unqualified samples are tested at 12 GHz and 18 GHz, respectively. From Fig. 9, we can find that the attenuation distributions of the qualified and unqualified thin-films are different, especially in the maximum attenuation section. In the actual application, it is better to choose a standard qualified dielectric rod as a reference for the attenuation evaluation. If the attenuation of the measured dielectric rod is less or greater than the reference value, the dielectric rod will be unqualified.

In this paper, we simply deduce and analyze the E-field distribution in the parallel strip, and we draw the conclusion that it is similar to the actual E-field in TWT. Furthermore, we designed a modified fixture to provide a relatively reasonable field environment for the attenuation evaluation. We also designed an arcuate taper for the fixture, which is proved to be useful to reduce the impedance mismatching caused by the sample hole. The attenuation measured results of the qualified and unqualified dielectric rods at 12 GHz and 18 GHz verified that the proposed fixture is feasible to evaluate the qualification of the dielectric rods coated with a thin-film.

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