Analysis of Microstrip Coupling Gap to Estimate Polymer Permittivity

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Abstract—A gap in the microstrip line can be modeled as a π-network of capacitances. The series gap capacitance depends on the permittivity of the polymer that fills the gap. We propose modification to the model so that permittivity of the polymer gets incorporated in it. Using this model, we can estimate the permittivity of the polymer from the transmission coefficient of two-port network.

Keywords—Coupling gap; π-network; transmission coefficient; organic polymer

I. INTRODUCTION

Gaps in the conducting strips of microstrip transmission lines are used in microwave circuits such as capacitors, DC blocks, radiating elements, and in measurement systems. They are very suitableelements for monolithic and hybrid microwave integrated circuits. The study of gap in microstrip line is useful in the design of DC blocks, coupled filters and coupling element to resonators etc.

In a microstrip circuit, the dielectric media above the circuit is usually air and the dielectric below the circuit is the substrate material. With air as the dielectric above the circuit, the dielectric constant ε_r of the substrate and the effective dielectric constant ε_{eff} of the microstrip are related by a filling factor that weighs the amount of the field in air and the amount of field in the dielectric substrate. As in a microstrip transmission line, the electric field is concentrated between the strip and the ground plane and a weak fringing field exists beyond the dielectric substrate. One of the techniques to increase the interaction of the polymer with the fields would be to introduce the polymer in the gap of the transmission line as there are strong fringing fields at the open ends of the gap.

In this paper, we analyze straight gap discontinuity in a microstrip transmission line, and the effect of changing the permittivity of the material which fills the gap, on the scattering parameters of the two-port structure. The polymer changes the gap capacitance, which is a function of the permittivity of the polymer. So by measuring the terminal scattering parameters, it is possible to estimate the gap capacitance and hence to estimate the permittivity of the polymer. One of the great advantages of this method compared to the other techniques is that very small quantity (as much required to fill the gap) of sample is required to make the measurement.

II. STRAIGHT GAP IN MICROSTRIP TRANSMISSION LINE

A. Gap Discontinuity- Equivalent Circuit

The gap discontinuities in microstrip lines have the abrupt change in the dimension of the strip conductor, which gives rise to a change in the electric field and magnetic field distributions. The straight gap discontinuity in microstrip line is shown in Fig.1, generally represented as a π-equivalent circuit with three capacitive elements [1]. The standard equivalent circuit representation of gap discontinuity in microstrip transmission line is as shown Fig.2 (a), where A_T denotes the ABCD matrix for the transmission line section and A is the ABCD matrix of π-equivalent circuit of the gap discontinuity.

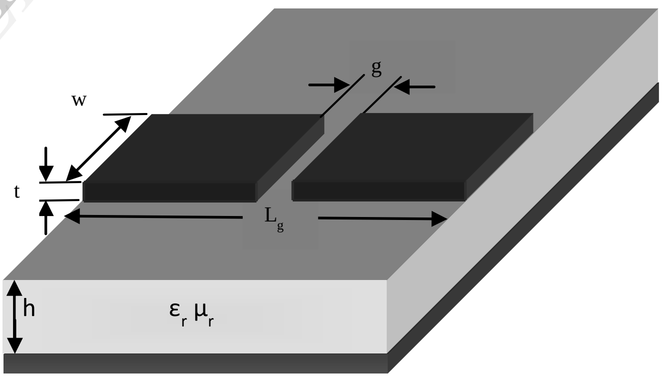


Fig.1. Gap discontinuity in microstrip transmission line.

TABLE1. PARAMETERS OF SUBSTRATE USED TO ANALYZE GAP DISCONTINUITY

Parameter	Symbol	Value
Frequency	f	2 - 3GHz
Width of line	w	0.373mm
Height of substrate	h	0.254mm
Thickness of copper strip	t	0.035mm
Coupling gap	g	0.2mm
Total length	L_g	35mm
Dielectric constant of the substrate	ε_r	6.15

The shunt capacitance C_1 is the result of the disorder in electric field distribution at the edge of the strip. The series capacitance C_2 arises from the coupling between the strip conductors constituting the gap. C_2 reduces with the increase in gap spacing and for infinite spacing C_2 approaches zero and C_1 equals the end-capacitance for an open-ended line.

The parameters of the substrate used to analyze the microstrip gap discontinuity are listed in TABLE1, which satisfy the conditions $2.5 \leq \varepsilon_r \leq 15$ and $0.5 \leq w/h \leq 2$ for π-network standard equivalent circuit formulation, as given by Eq. (1) to Eq. (12).

The standard equivalent circuit capacitances C_1 and C_2 are expressed in terms of C_{even} and C_{odd} as given by Eq. (1) to Eq. (4) [2].

$$C_{even} = 2 * C_1 \tag{1}$$
$$C_{odd} = 2 * C_2 + C_1 \tag{2}$$
$$C_1 = 0.5 * C_{even} \tag{3}$$
$$C_2 = 0.5 * C_{odd} - 0.25 * C_{even} \tag{4}$$

whereC_{even} and C_{odd} are the equivalent circuit parameters for the gap when it is excited symmetrically and anti-symmetrically. The closed form expression for C_{even} and C_{odd} when $2.5 \leq \varepsilon_r \leq 15$ and $0.5 \leq w/h \leq 2$ are satisfied, is given by Eq. (5) and Eq. (6).

$$C_{odd}(\varepsilon_r) = w * \left(\frac{\varepsilon_r}{9.6}\right)^{0.8} * \left(\frac{g}{w}\right)^{m_o} * \exp(k_o) \tag{5}$$
$$C_{even}(\varepsilon_r) = w * \left(\frac{\varepsilon_r}{9.6}\right)^{0.9} * \left(\frac{g}{w}\right)^{m_e} * \exp(k_e) \tag{6}$$

Here

$$m_o = \left({}^{w}/_{h}\right) * \left[0.619 * log_{10}\left({}^{w}/_{h}\right) - 0.3853\right] \tag{7}$$
(for $0.1 \leq g/w \leq 1.0$)

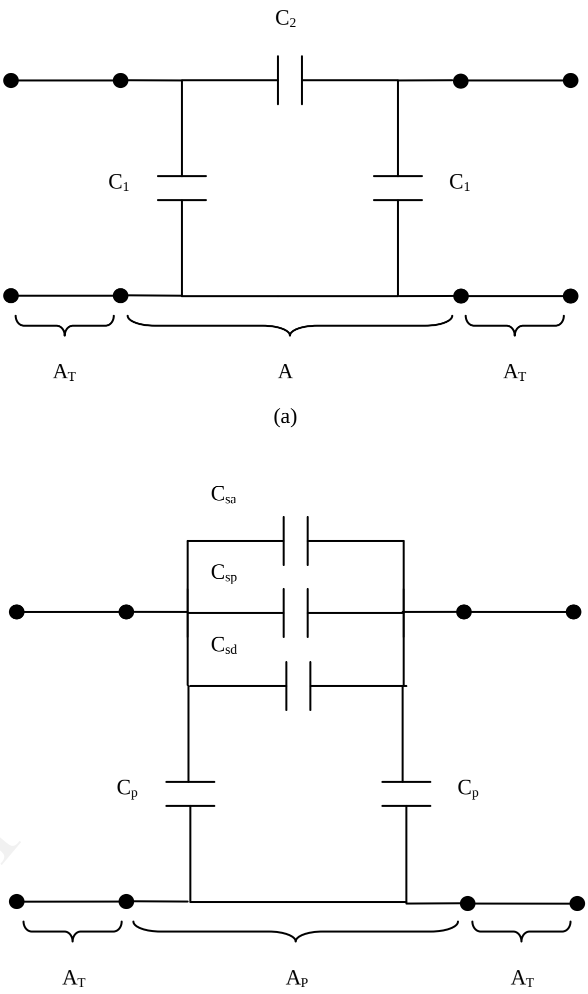
$$k_o = 4.26 - 1.453 * log_{10}\left({}^{w}/_{h}\right) \tag{8}$$
(for $0.1 \leq g/w \leq 1.0$)

$$m_e = 0.8675 \tag{9}$$
(for $0.1 \leq g/w \leq 0.3$)

$$k_e = 2.043 * \left({}^{w}/_{h}\right)^{0.12} \tag{10}$$
(for $0.1 \leq g/w \leq 0.3$)

$$m_e = \frac{1.565}{\left({}^{w}/_{h}\right)^{0.16}} - 1 \tag{11}$$
(for $0.3 \leq g/w \leq 1$)

$$k_e = 1.97 - \frac{0.03}{\left({}^{w}/_{h}\right)} \tag{12}$$
(for $0.3 \leq g/w \leq 1$)



(a)

(b)

Fig.2. Equivalent circuit representation of gap discontinuity in microstrip transmission line (a) standard equivalent circuit and (b) improved equivalent circuit.

The standard equivalent circuit capacitances C_1 and C_2 arecalculated using bahl_formula.m m-file for substrate parameters as listed in TABLE1.

This formulation does not really represent the gap because no allowance is made for the discontinuity filled via polymer in the equivalent lumped parameters. Hence a multi-element equivalent network is proposed as shown in Fig.2 (b) [3], where A_T denotes the ABCD matrix for the transmission line section and A_P is the ABCD matrix of π-equivalent circuit of the gap discontinuity filled with polymer. The improved equivalent circuit has gap capacitance corresponding to the discontinuity and takes the effect of changing the permittivity of the material that fills the gap into account.

B. Gap Filled With Polymer – Improved Equivalent Circuit

The improved equivalent circuit of the microstrip line having gap filled with polymer is shown in Fig.2 (b). Fig.3 shows the gap discontinuity in microstrip transmission line filled with organic polymer and Fig.4 shows the corresponding cross sectional view.

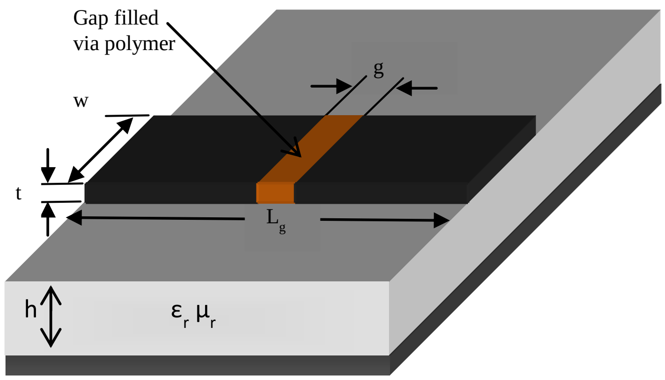


Fig.3. Gap discontinuity in microstrip transmission line filled with organic polymer.

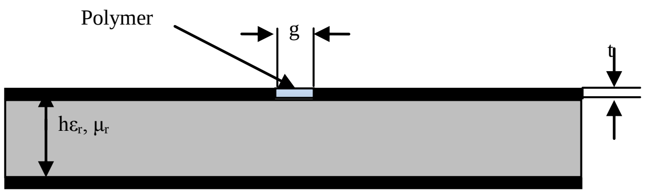


Fig.4. Cross sectional view of gap discontinuity in microstrip transmission line filled with organic polymer.

To calculate the gap capacitances for the discontinuity filled via polymer, semi-empirical relations are developed. Starting with an approximation that the standard formulation is valid for air (ε_r=1), the gap capacitances (C_{sa1}, C_{sp1}, C_{sd1}, C_{p1}) are calculated for the discontinuity in microstrip transmission line having air as dielectric substrate, then the gap capacitances (C_{sa2}, C_{sp2}, C_{sd2}, C_{p2}) for the discontinuity inmicrostrip transmission line having dielectric substrate withε_r=6.15 are formulated, using these the gap capacitances for the discontinuity filled with polymer (C_{sa3}, C_{sp3}, C_{sd3}, C_{p3}), in microstrip transmission line having dielectric substrate for εr=6.15 are calculated. Thegapcapacitances (C_{sa3}, C_{sp3}, C_{sd3}, C_{p3}) are then used to calculate two-port scattering parameters of microstrip line gap filled with polymer by using new_equi.m m-file.

Fig.5 shows the equivalent circuit representation of the gap discontinuity in microstrip transmission line having air as dielectricsubstrate. As C_{sa1}, C_{sp1}, C_{sd1}, C_{p1} are the gap capacitances for the discontinuity, the standard equivalent circuit series gap capacitance C_{21} can be split into three parts as follows.

$$C_{21} = C_{sa1} + C_{sp1} + C_{sd1} \tag{13}$$

where C_{sa1} is capacitance of the fringing fields in air, C_{sp1} is parallel plate capacitance of the gap as filled with air, C_{sd1} is capacitance of the fringing fields inside the dielectric substrate material which is air in this case.

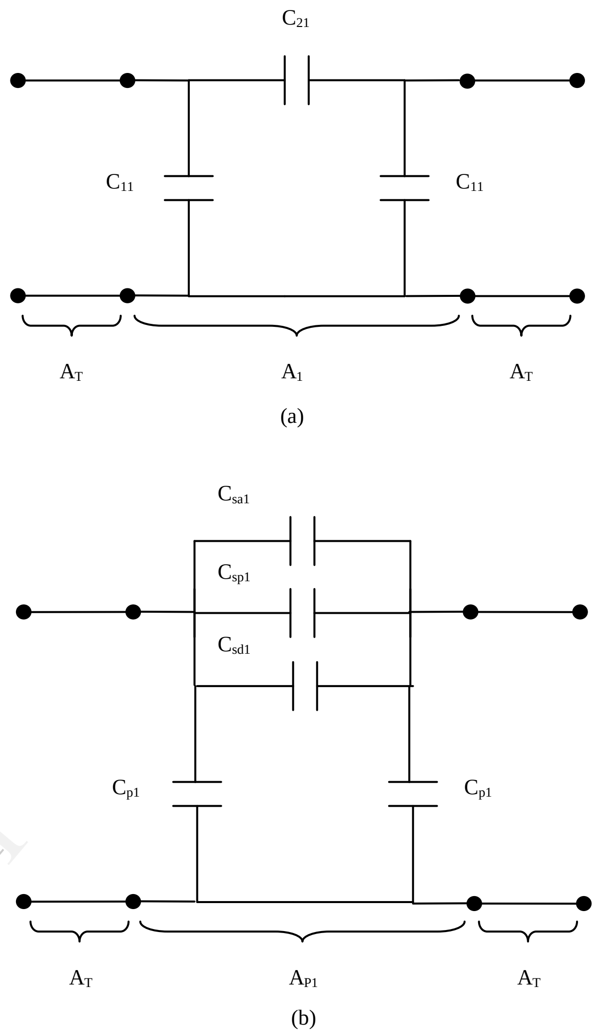


Fig.5. Representation of gap discontinuity in microstrip transmission line having air as dielectric substrate (a) standard equivalent circuit and (b) improved equivalent circuit.

As C_{sa1} depends on the physical parameters and C_{sd1} is a function of the dielectric properties of the material between the strip and the ground plane of the microstrip line (air as dielectric substrate in this case).

$$C_{sd1} = C_{sa1} \tag{14}$$
$$C_{sp1} = \varepsilon_o tw/g \tag{15}$$
$$C_{sa1} = 0.5 * (C_{21} - C_{sp1}) \tag{16}$$
$$C_{p1} = C_{11} \tag{17}$$

where C_{p1} is capacitance of the fringing fields between the strip edge and the ground plane through air. Fringing capacitance is the capacitance of a line’s edges i.e. the increased capacitance beyond the ideal parallel plate capacitance due to edge fields that do not reach from one edge to the other.

Fig.6 shows the equivalent circuit representation of the gap discontinuity in microstrip transmission line having dielectric substrate corresponding to ε_r=6.15. The standard equivalent

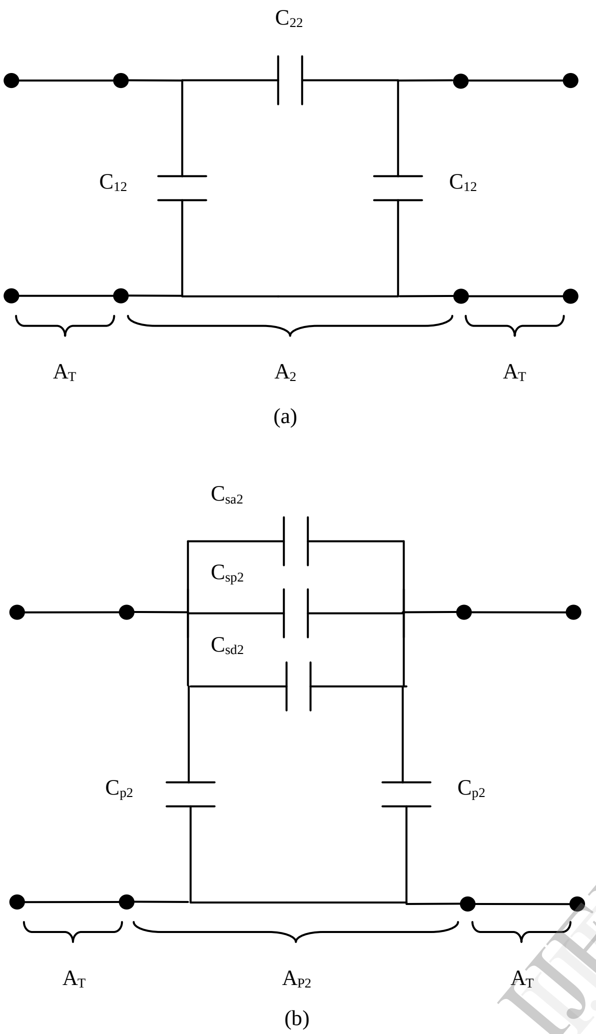


Fig.6. Representation of gap discontinuity in microstrip transmission line having dielectric substrate (εr=6.15) (a) standard equivalent circuit and (b) improved equivalent circuit.

circuit series gap capacitance C_{22} can be split into three gap capacitances as C_{sa2}, C_{sp2} and C_{sd2} as given by Eq. (18).

$$C_{22} = C_{sa2} + C_{sp2} + C_{sd2} \tag{18}$$
$$C_{sa2} = C_{sa1} \tag{19}$$
$$C_{sp2} = C_{sp1} = \varepsilon_o tw/g \tag{20}$$
$$C_{sd2} = C_{22} - C_{sp2} - C_{sa2} \tag{21}$$
$$C_{p2} = C_{12} \tag{22}$$

where C_{p2} is the fringing field capacitance for a dielectric substrate.

Fig.7 shows the equivalent circuit representation of the gap discontinuity in microstrip transmission line having dielectric substrate corresponding to ε_r=6.15, filled with organic polymer. C_{sa3}, C_{sp3}, C_{sd3} and C_{p3} are the improved equivalent circuit gap capacitances when discontinuity in microstrip transmission line having dielectric substrate, is filled with organic polymer. Now the standard equivalent circuit series gap capacitance C_{23} is given by Eq. (23) and plate capacitance C_{sp3} is given by Eq. (24).

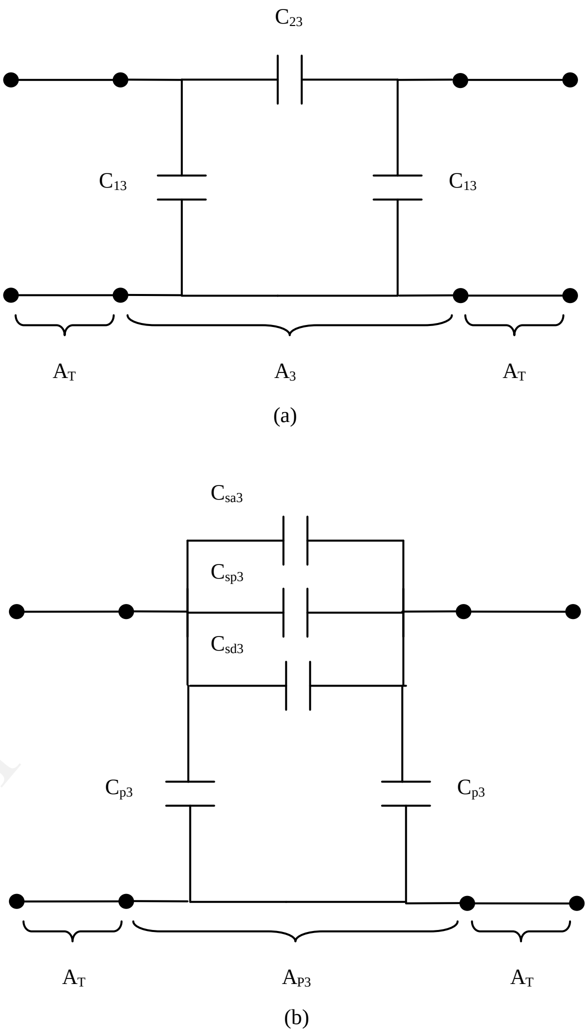


Fig.7. Representation of gap discontinuity filled with polymer in microstrip transmission line having dielectric substrate (εr=6.15) (a) standard equivalent circuit and (b) improved equivalent circuit.

$$C_{23} = C_{sa3} + C_{sp3} + C_{sd3} \tag{23}$$
$$C_{sp3} = (\kappa)^{0.85}\, \varepsilon_o tw/g \tag{24}$$

where κ is the permittivity of the polymer filling the microstrip line gap, ε_0 is the free space dielectric constant, t is thickness of the conducting strip at the gap, g is the width of the gap and w is the width of the conducting strip.

$$C_{sa3} = C_{sa2} \tag{25}$$
$$C_{sd3} = C_{sd2} \tag{26}$$
$$C_{p3} = C_{p2} \tag{27}$$

The series capacitance in the improved equivalent circuit depends on the permittivity of the polymer that fills the gap, so has an effect on the scattering parameters of the two-port structure. Now we can compute the ABCD matrices corresponding to the transmission line (A_T) and π-equivalent circuit of the gap discontinuity filled with polymer (A_{P3}). The matrix product (A_T $A_{P3}A_T$) gives the overall ABCD matrix of the microstrip transmission line structure having gap discontinuity. From this, we can compute the two-port scattering parameters of the structure. Using EM simulation tool (IE3D) we can computed the scattering parameters.

III. RESULT AND DISCUSSION

A comparison of $|S_{12}|$ computed using the equivalent circuit and EM simulation tool is shown in Fig.8. Fig.8 shows the variation of $|S_{12}|$ with κ for microstrip gap discontinuity when gap is filled with polymer, where κ symbolizes the permittivity of the polymer filling the gap. The plots with markers on lines correspond to simulated $|S_{12}|$ for different values of κ, while plots without markers correspond to $|S_{12}|$ response, obtained using new_equi.m m-file.

The difference between the $|S_{12}|$ obtained using EM simulation and $|S_{12}|$ computed using proposed equivalent circuit can be accounted due to the approximation made in the standard formulation for air (ε_r=1), to find the gap capacitances (C_{sa1}, C_{sp1}, C_{sd1}, C_{p1}) for the discontinuity in microstrip transmission line having air as dielectric substrate.

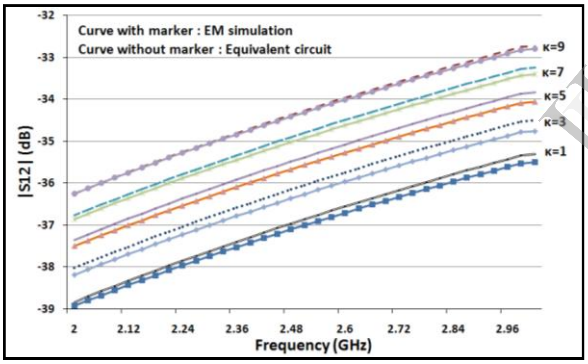


Fig.8. Magnitude of transmission coefficient of gap discontinuity filled with polymer showing the effect of κ.

The two-port scattering parameter response is sensitive to the change in the permittivity of the polymer (κ) filling the discontinuity in microstrip transmission line and can be used to estimate the permittivity of the polymer. For example, if the measured $|S_{12}|$ versus frequency is provided, we can estimate permittivity by minimizing the difference between the measured and calculated scattering parameters ("in press"**Error! Reference source not found.**). In this optimization process, the only unknown is the permittivity of the polymer. The main advantage of using the equivalent circuit rather than an EM simulation tool to compute the scattering matrix is the speed.

IV. CONCLUSION

In this paper we present a modified equivalent circuit for a gap discontinuity in a microstrip line. The modification takes into account the effect of dielectric filling the gap. We demonstrate the accuracy of the equivalent circuit by comparing the transmission coefficient computed using EM simulation and $|S_{12}|$ computed using proposed equivalent circuit. Using the equivalent circuit to compute the scattering parameters rather than EM simulation will considerably reduce the time required to estimate the permittivity using an optimization procedure.

The proposed equivalent circuit is able to predict the transmission coefficient reasonably well, though there is scope for improvement.It is rather difficult to fill the gap completely with polymer due to surface tension, there could be voids in the filling and hence affects the accuracy of estimation of permittivity.

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