SAND2019-1606C

Design and Characterization of Meshed Microstrip Transmission Lines

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***Abstract*—Advancements in manufacturing techniques have enabled the ability to create micro-mesh conductive structures which have applications in a variety of electrical engineering technologies. This paper presents the theoretical analysis verified with simulated results and laboratory measurements of a 2.4 GHz micro-mesh transmission line over a solid ground plane. As expected, the reduction in conductive area results in a decrease in capacitance per unit length, and the mesh structure results in an increase in inductance per unit length leading to an overall increase in characteristic impedance and increase in electrical length. Results show that the mesh implementation to reduce the conductive material to 16% on a microstrip transmission line using FR-4 must get 44% wider than its solid metal counterpart to maintain 50 Ω impedance. Length must be similarly increased by a factor of 4% to maintain the same electrical length.**

Index Terms*—*Meshed transmission lines, effective permittivity, microstrip transmission lines, characteristic impedance

I. Introduction and Background

MESH conductors are being introduced in microwave engineering as an alternative conductor for various purposes including cost savings, weight reduction, and even a method for transparent conductors [1]. In many applications to date, meshed transmission lines (TLs) have not been considered as most microstrip TLs are fabricated by milling out the conductor, which makes meshed conductors impractical due to increased fabrication time. With advancements in technologies like ink-jet printing, laser etching, and micro-fabrication, mesh conductors have become much more feasible and in some applications, a necessity.

In studies on solid microstrip TLs with meshed ground planes, changes in the inductance, capacitance, and thus a change impedance have been observed when compared to solid structures [2, 3]. Meshed patch antennas have also shown a shift in resonant frequency compared to solid patches when the mesh parameters (pitch, line width, etc.) are changed [4]. The observations of the changes in the response in the literature are consistent, but have yet to be studied in depth. Impedance extraction has been successfully performed from the S-parameters using the ABCD conversion to get the impedance of TLs reference to a meshed ground [5].

Though the physical characterization has not been studied, meshed structures have been shown to be useful embedded on solar panels to allow light to pass through allowing for low-profile antennas aboard CubeSats [6, 7]. Honeycomb mesh transmission lines with a meshed ground plane have also been observed on flexible glass at 80 GHz. It performed with less than 1 dB insertion loss (IL) and was implemented as the feed for a patch antenna which radiated at 83 GHz [8]. Mesh conductors at microwave frequencies are opening up the design space for solutions to problems that were once limited by a solid conductor.

The paper will discuss the microstrip transmission line and explore how the design equations must be modified when meshed. This approach lays the foundation for design of new structures such as mesh antennas or mesh filters. The following study presents the response of transmission line parameters when a mesh is introduced and its comparison versus the standard solid conductor trace. The following sections will investigate the effects of a meshed trace referenced to a solid ground plane. The inductance, capacitance, effective permittivity, and impedance will be examined for different mesh parameters.

II. Microstrip Transmission Line

Microstrip TLs are widely used in RF and microwave engineering and are used for transferring high frequency energy in quasi-TEM form. TLs at high frequencies are known to have the form of an RLGC circuit, where R is resistance per unit length, L is inductance per unit length, G is conductance per unit length, and C is capacitance per unit length [9]. The capacitance is due to the proximity of the conductors, and the inductance represents the self inductance of the signal trace and the ground plane. In practical designs, the loss of the TL is negligible allowing R and G to be neglected. As a result, they won't be discussed in the analysis in this paper. Important microstrip line parameters such as phase velocity, propagation constant, characteristic impedance and the RLGC parameters can be extracted from the S-parameters using S-parameters to Z and Y parameter identities. The RLGC parameters give the approximate propagation constant; characteristic impedance Z_c shown in (1); operating frequency shown in f (2); and phase velocity of the TL.

In addition to the RLGC parameters, effective permittivity is an important quantity which governs much of the propagation behavior and determine impedance and phase length to design an RF microstrip circuit [10]. The effective permittivity ϵ_e can be computing using (3), where ϵ_r is the relative permittivity,

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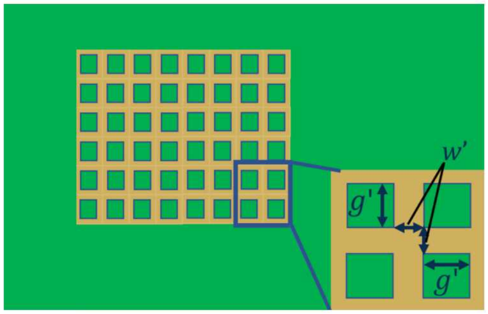


Fig. 1: Fill factor unit cell depicting the pitch g' and the linewidth w'.

W is the width of the transmission line, and d is the height of the substrate. [10]. In addition, the phase ϕ of the transmission line can be found using (4), where k_0 is the propagation constant in air, and l is the length of the transmission line.

$$Z_c = \sqrt{\frac{L}{C}} \tag{1}$$

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{2}$$

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + \frac{12d}{W}}} \tag{3}$$

$$\phi = \sqrt{\epsilon_e} k_0 l \tag{4}$$

III. Meshed Transmission Line

Introducing a mesh to a TL will likely cause changes to the properties of the TL, even when obeying the Rayleigh criterion. The mesh alters the inherit capacitance and inductance of the solid TL. Basic electromagnetic theory suggests a meshed transmission line will decrease the capacitance and increase inductance based on the geometrical aspects of the mesh. From the geometry of the microstrip TL, one would expect the capacitance to decrease and the inductance to increase as the fill factor decreases (as more metal is removed). If inductance increases and capacitance decreases, from (1) Z_c increases.

A. Fill Factor

Fill factor Ψ is a unitless quantity that falls between 0 and 1, and is defined in (5) where w' is the line width and g' is the gap or line spacing shown in Fig 1. Fill factor is a measure of the ratio of conductor to open space [11]. This value is key to compare the effects on mesh size and spacing in parameter sweeps by relating the line width and pitch to a single quantity which allows for a simpler comparison. Fill factor is also related to transparency T, where $T = 1 - \Psi^2$. It must be noted that (5) is only valid for a symmetric square unit cell and must be redefined for a rectangular cell.

$$\Psi = \frac{w'}{g' + w'} \tag{5}$$

B. Proposed Modification to Effective Permittivity

Introducing a mesh to a microstrip TL signal trace will affect the effective permittivity as a function of the fill factor. Equation (6) for the effective permittivity of a mesh region of a transmission line ϵ_e^{mesh}, includes the fill factor and will be verified in the Section V. The modification allows the open area of the mesh to be taken into account in the effective permittivity for BB' of Fig. 2a. The $\sqrt{\Psi}$ in (6) can be described by the physical phenomena where the mesh added an electrical width to the transmission line due to the fringing fields of the TL which increase in the mesh due to the added inductance within the trace, and the decreased capacitance between the trace and the ground plane.

$$\epsilon_e^{mesh} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + \frac{12d\sqrt{\Psi}}{W}}} \tag{6}$$

Equation (7) gives the total effective permittivity computed as a weighted average of section AA' in Fig. 2b given by (3) and section BB' in Fig. 2b given by (6).

$$\epsilon_e^{total} = \epsilon_e \Psi + \epsilon_e^{mesh}(1 - \Psi) \tag{7}$$

IV. Simulation vs Measurement

Two microstrip TL models were simulated, fabricated, and measured. The board was made using copper conductor, FR4 substrate ($\epsilon_r = 4.6$) with thickness 1.6 mm as shown in Fig. 3. Table I shows the design parameters for both transmission line structures. The solid transmission line, trace 1, was designed to be 50 Ω and the meshed transmission line kept the trace width constant to later analyze the effect of the mesh on a TL of the same dimensions. The simulations were carried out in CST Microwave Design Suite and fabricated board was made by Oshpark. Simulation and measurement of the mesh and solid

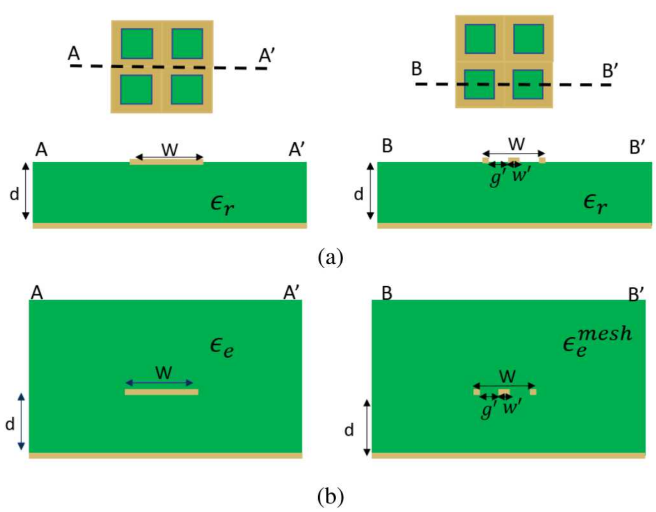


Fig. 2: (a) Unit cell with cross section of dielectric and air interface. AA' is the portion with solid TL. BB' is the portion with an open gap in the transmission line. (b) Cross section showing the effective permittivity covering the full region of the transmission line.

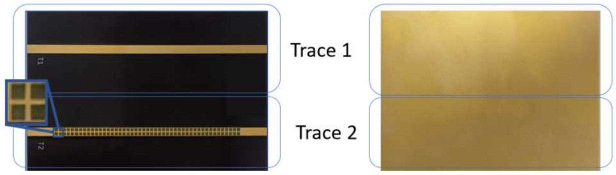


Fig. 3: Fabricated board with the solid TL (Trace 1) and the meshed TL (Trace 2).

TABLE I: Solid TL and meshed TL design parameters.

	Solid TL	Mesh TL
Thickness, d	1.6 mm	1.6 mm
ϵ_r	4.6	4.6
Trace Width, W	2.92 mm	2.92 mm
Length	88.95 mm	88.95 mm
Fill Factor, Ψ	1	0.21
Mesh Spacing, g'	—	1.15 mm
Mesh Line Width, w'	—	0.31 mm

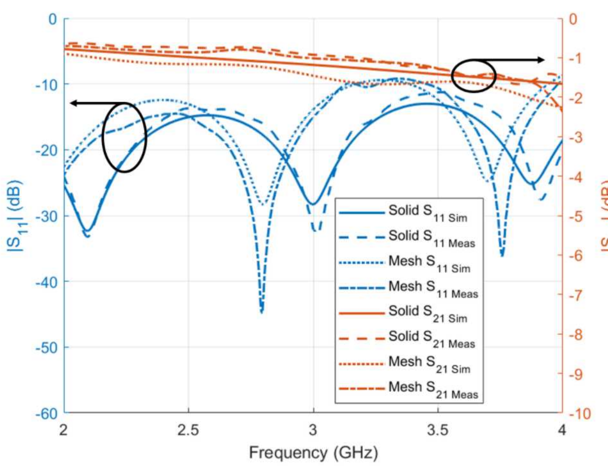
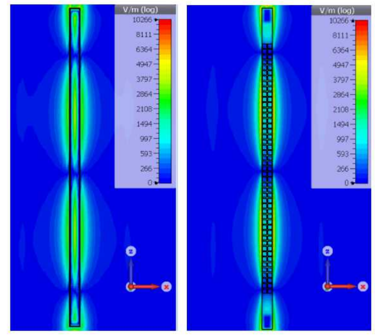


Fig. 4: Simulated and measured TL $|S_{11}|$ reference left axis and $|S_{21}|$ reference right y-axis. Measured data for the solid and mesh TLs shown in Fig. 3.

TL are shown in Fig. 4. The solid TL was designed to have $|S_{11}|$ below -10 dB from 2 to 4 GHz. The measured data shows agreement with the simulation which allows for a parametric study to be carried out using the mesh TL. In simulation and measurement of the meshed transmission line, a shift in the return loss (RL) is evident from 3 GHz in the solid TL to 2.7 GHz in the meshed TL. The IL in Fig. 4 shows a larger loss in the meshed transmission line in both the simulation and measurement at 2.4 GHz, but only by about 0.1 dB between the solid and meshed transmission line measurements and 0.2 dB in simulation. The initial S-parameters show there is likely a shift in the impedance and electrical length due to adding a mesh, but a further S-parameter extraction will be carried out in Section V to verify the results. Fig. 5a and 5b show the quasi-TEM field distribution in the solid meshed TL to display the propagation in simulation at 2.4 GHz which shows a small change within the meshed transmission line likely due to the added inductance due to the meshed lines.



(a) (b)

Fig. 5: Simulated electric field at 2.4 GHz of (a) solid TL (b) mesh TL with a solid ground plane

V. Meshed vs Solid Comparison

A parametric sweep was carried out which varied the fill factor but kept the unit cell size $g' + w'$ constant. Keeping the unit cell size constant allows the fill factor to be the only variable allowing the changes in geometry to be easily tracked in the parametric study. fill factor will be varied between 0.05 and 1.

Performing a fill factor parameter sweep, the RLCG parameters can be extracted at 2.4 GHz from the S-parameters. Of the RLGC parameters the L and C are most important to verify the intuition that the inductance would increase, and the capacitance would decrease as fill factor decreases. Table II shows the results in the L and C columns. As fill factor decreases, the L increases by $L \approx 46(pH/m)/\Psi$ and a decrease of $C \approx 13.7(fF/m)/\Psi$. The changes in L and C will create a frequency shift that can be seen in Fig. 4 since resonant frequency is given by (2).

TABLE II: Simulated TL parameters versus fill factor.

Ψ	S_{21} Phase, $\phi(^o)$	ϵ_e	L (nH/m)	C (pF/m)	Z_o (Ω)
0.05	-538.74	3.828	0.144	0.0298	69.6011
0.09	-536.75	3.758	0.143	0.0305	67.8986
0.21	-531.64	3.642	0.142	0.0317	64.9887
0.30	-528.16	3.596	0.137	0.0332	64.4353
0.42	-525.44	3.558	0.116	0.0355	57.0512
0.55	-523.97	3.534	0.114	0.0359	56.2787
0.66	-521.64	3.519	0.109	0.0370	54.3593
0.78	-521.63	3.510	0.108	0.0381	54.1933
1.00	-521.33	3.504	0.099	0.0397	50

Following the L and C parameters, the microstrip TL effective permittivity can be extracted using the phase information directly from the S-parameters using (4). The extracted permittivity can be compared to the calculated effective permittivity using (6) and (7). With the modification to account for fill factor Ψ the values of effective permittivity are able to be accurately predicted as shown in Fig. 6.

Based on the changes in capacitance and inductance, matching the meshed TL impedance to 50 Ω can be executed by increasing the width W of TL which will increase the capacitance while decreasing the inductance of the signal trace. Increasing the width from 2.92 mm to 4.3 mm (keeping other parameters the same from Table I) for a solid TL will

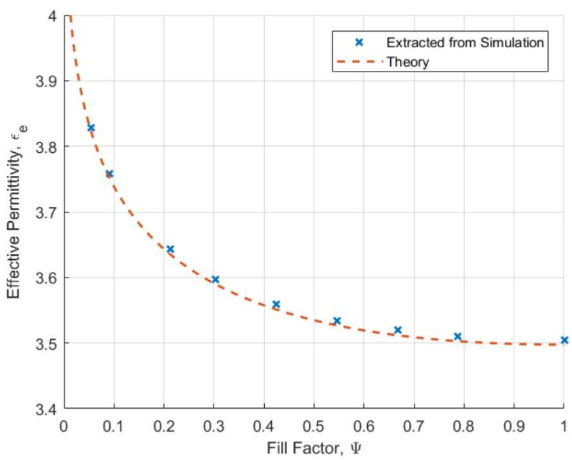


Fig. 6: Effective permittivity vs fill factor displaying theoretical and simulated values at 2.4 GHz.

increase the capacitance and decrease the inductance to lower the impedance from 50 Ω to 38 Ω, but applying mesh with parameters $\Psi = 0.16$, $g' = 1.8mm$ and $w' = 0.35$ will bring the impedance back up to 50 Ω to minimize reflections (RL below 25 dB) and IL around 0.9 dB at 2.4 GHz as displayed in Fig. 7. The phase length of the 50 Ω meshed TL goes up to 378° from 364.6° for a 50 Ω solid TL when the total length is 68.95 mm. Using the trends in Table II will allow for design equations to match a 50 Ω meshed TL of any fill factor.

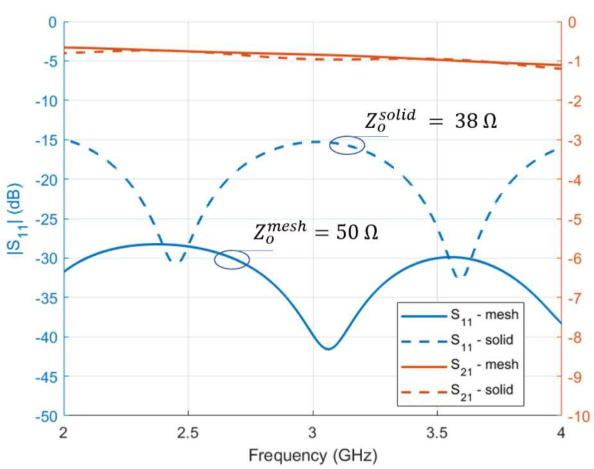


Fig. 7: Simulated S-parameters to match the meshed transmission line using a lower impedance solid transmission line as the reference. $W = 4.2mm$ $\Psi = 0.16$ for $S_{11}-$mesh and S_{21}-mesh.

VI. Conclusion and Future Work

This work has shown that introducing a mesh to a microstrip TL over a solid ground plane affects the TL. Specifically, ϵ_e is shown to increase as more metal is removed or the fill factor decreases. The L increases due to the introduction of new current paths and the C decreases due to the decrease in conductor cross sectional area. Since the results show that adding the mesh to the solid TL will increase the impedance, the TL must be made with a smaller width to account for the increase in impedance to avoid reflections in an RF system.

Though in this paper a meshed TL with a solid ground plane was discussed, work to design and characterize a meshed ground plane with a meshed trace is of interest for transparent RF problems at higher frequencies. To achieve a transparent antenna using the metal mesh, a mesh ground plane must also be present. The future analysis likely follows the same trends presented in this paper.

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