High Signal Integrity Transmission Lines Enabled with Thin Films and Design Techniques

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***Abstract*— This report presents innovative methodologies enabled with thin films and design techniques to mitigate far-end crosstalk (FEXT) in transmission lines. These methodologies consist of transmission line structures featuring non-uniform signal conductor thickness, as well as the integration of high permittivity dielectric thin films and high permeability magnetic thin films. Furthermore, the efficacy of the proposed high signal integrity transmission lines is comprehensively studied by employing both equivalent circuit and formulaic modelling.**

***Index Terms*—Signal integrity, Far-end crosstalk (FEXT), Interconnects, Thin films**

I. INTRODUCTION

WITH the rapid evolution of fifth-generation (5G) and beyond communication systems, the burgeoning wireless communication market is propelling integrated circuits and devices towards the trend of smaller sizes, higher speeds and frequencies. The signal traces are thus required to be closely placed within a limit space, rendering them susceptible to electric and magnetic coupling, thus generating interference caused by electromagnetic signals affecting adjacent electronic signals, a phenomenon known as crosstalk. Electromagnetic crosstalk poses a significant challenge in electronic systems, especially with the increasing demand for miniaturization, which leads to high-speed circuitry being in proximity. Furthermore, the escalation of far-end crosstalk (FEXT) along the signal channel exacerbates signal integrity issues for receiving signals. Consequently, there is a critical need for methodologies to mitigate FEXT for modern communication systems.

Although technical solutions for reducing FEXT have been extensively investigated and successfully demonstrated [1], current techniques still face limitations in further improving the inherent capacitance and inductance to continuously miniaturize the FEXT, due to the geometric and process constraints. This report analyzes the FEXT of interconnects in proximity, using formulaic models and proposes innovative methods to further mitigate FEXT. Specifically, the report explores techniques including transmission line structures with non-uniform signal conductor thickness, integration of high permittivity dielectric thin films and high permeability magnetic thin films [2].

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II. PROJECT OUTCOME

As illustrated in Fig.1, a typical transmission lines structure is first analyzed with their equivalent LC circuit model. Line A is considered as the aggressor line while line B is the victim line. Port 1 serves as the signal input and port 4 receives the FEXT, which can be defined as

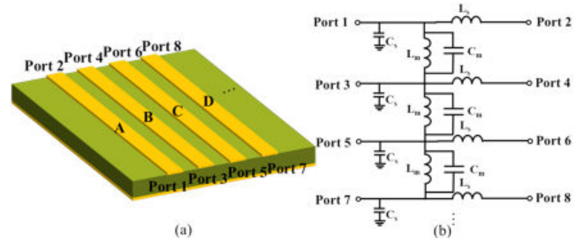

Fig. 1. (a) Transmission lines structure and (b)its equivalent circuit.

$$FEXT = \frac{V_{in} l}{RT} \times \frac{1}{2v} \times \left(\frac{C_m}{C_s} - \frac{L_m}{L_s} \right), \tag{1}$$

where V_{in} is the input voltage, l is the physical length of the signal trace, RT is signal rise time, v is signal velocity, C_m is mutual capacitance between two traces, C_s is self-capacitance, L_m is mutual inductance between two traces, L_s is self-inductance. The mutual capacitance and inductance induced by nonadjacent lines are comparatively minor in comparison to those induced by adjacent ones, thus are omitted in this model. The far-end coupling coefficient can be expressed as

$$k_f = \frac{1}{2v} \times \left(\frac{C_m}{C_s} - \frac{L_m}{L_s} \right). \tag{2}$$

The self-capacitance can be expressed as

$$C_{si} = C_{pi} + C_{fi} + C_{fei},\ i\text{=1-4}, \tag{3}$$

where C_{pi}, C_{fi}, and C_{fei} denote as parallel plate capacitance, external fringing capacitance, and internal fringing capacitance, respectively. The mutual capacitance between each trace can be expressed as

$$C_m = C_{ma} + C_{mp} + C_{ms}, \tag{4}$$

where C_{ma} is the gap capacitance in the air above the transmission lines configuration, C_{mp} is the parallel plate capacitance between the transmission lines, C_{ms} is and the gap capacitance within the substrate. They can be expressed as

$$C_{ma} = \varepsilon_0 \frac{K(k')}{K(k)} - \Delta C_f, \tag{5}$$

$$C_{mp} = \varepsilon_0 \frac{t}{s}, \quad (6)$$

$$C_{ms} = \sqrt{C_{d1} C_{d2}}, \quad (7)$$

where t is the copper thickness, s is the spacing between traces, k is dimension related factor and $k' = \sqrt{1-k^2}$, ΔC_f is an empirical air-gap capacitance correction factor, $K(x)$ is the complete elliptical integral of the first kind. C_{di} are described in [3]. The inductance can be expressed as

$$L = \begin{bmatrix} L_s & L_m \\ L_m & L_s \end{bmatrix} = \frac{1}{v^2} \cdot \begin{bmatrix} C_s + C_m & -C_m \\ -C_m & C_s + C_m \end{bmatrix}^{-1}. \quad (8)$$

To reduce the FEXT, trapezoidal tabs are added along the transmission lines. These tabs introduce additional mutual capacitances C_{tab1} and C_{tab2}. Among them, C_{tab1} refers to the capacitance between tabs, which can be calculated by Eq. (4)-(7). The C_{tab2} refers to the fringe capacitance between the tabs end and the trace, which can be expressed as

$$C_{tab2} = \frac{1}{2} \cdot \left(\frac{1}{c_0 Z_t} - \varepsilon_0 \frac{l_1 + l_2}{(s - 2s_1)} \right), \quad (9)$$

where Z_t is the characteristic impedance of the single-ended microstrip line with air as substrate, l_1 and l_2 are the upper and lower widths of the tabs, respectively, and s_1 is the distance between tab end and trace.

Based on the above theoretical analysis, it is obvious that as the ratio of $\frac{C_m}{C_s}$ approaches to $\frac{L_m}{L_s}$, the FEXT can be eliminated, and effective approaches to achieving it is by enhancing C_m or L_s values. To practically implement this concept, methodologies are proposed, which are illustrated in Fig. 2(a)-

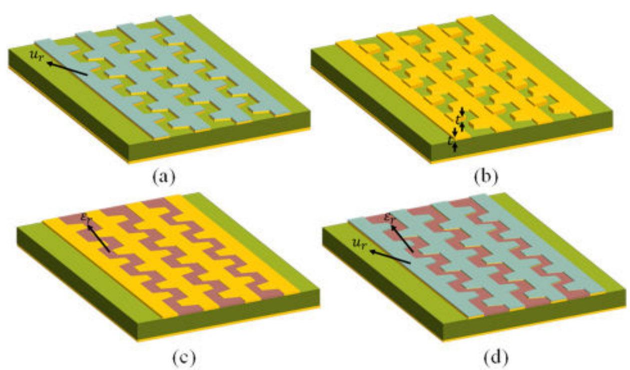

Fig. 2. (a) Method 1 covered magnetic material on traces, (b) Method 2 thickened tabs, (c) Method 3 filled dielectric material between traces, and (d) Method 4 covered magnetic material on traces and filled dielectric material between traces.

(d), showcasing covering magnetic material on traces (Method 1), thickening tabs (Method 2), filling dielectric material between traces (Method 3), and combining both magnetic material on traces and dielectric material between traces (method 4). According to the equivalent circuit analysis and formulaic models, Method 1 aims to enhance self-inductance, while Method 2 and 3 seek to enhance mutual capacitance utilizing thickened tabs and dielectric materials, respectively. Method 4, on the other hand, integrates dielectric and magnetic materials to enhance both mutual capacitance and self-inductance. To validate the efficacy of these proposed methods, comparisons of inductance and capacitance values and FEXT performance are presented in Table I and Fig. 3. The maximum FEXT can be improved by 36.75 dB via Method 4, while the original tabbed routing can only improve by 14.03 dB at 10 GHz.

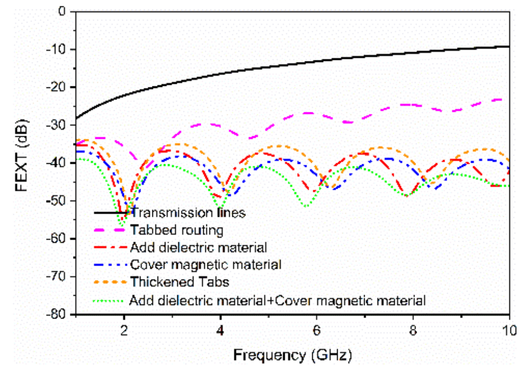

Fig. 3. Comparison of FEXT among four different transmission line structures, tabbed routing and regular coupled line benchmark.

TABLE I COMPARISON OF CAPACITANCE, INDUCTANCE, $|K_F|$ AND FEXT REDUCTION FOR DIFFERENT STRUCTURES

Cases	C_m pf	C_s pf	L_m nH	L_s nH	$\|k_f\|$ $\times 10^{-11}$	FEXT Reduction @10 GHz
Transmission lines	0.12	4.24	0.85	10.98	13.96	/
Tabbed routing	0.31	5.00	0.89	10.60	7.11	14.03 dB
Thickened Tabs	0.55	5.20	0.93	10.43	5.42	30.20 dB
Dielectric material	0.55	5.45	0.89	10.60	5.57	32.88 dB
Magnetic material	0.31	5.00	0.61	12.12	3.83	32.34 dB
Dielectric &magnetic material	0.41	5.16	0.82	11.05	2.82	36.75 dB

III. CAREER PLAN AND FELLOWSHIP IMPACT AND ACKNOWLEDGEMENT

After completing my doctoral studies, I will continue my research in pursuit of advancing the field of RF/ microwave engineering. The recognition of receiving this prestigious award has motivated me to push the boundaries of this field further. I am deeply grateful to the IEEE MTT-S community for this honor and for sponsoring my attendance at the 2023 IMS in San Diego, CA, USA. I would also like to thank my advisor Dr. Guoan Wang for the encouragement and guidance throughout my research journey.

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