Fast Estimation of Radiated Emission from Microwave Microstrip Amplifiers

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***Abstract*: Simplified closed-form expression for microstrip-line radiation is derived and embedded in a commercial circuit solver for fast simulation of radiation from a microwave amplifier in this paper. According to two exemplifying cases, the results calculated by the simplified expression are close to the rigorous expression adopting the dyadic Green function. The expression is also verified by measurement performed inside an anechoic chamber. Therefore, the expression-embedded circuit solver is convincible and efficient in designing low-radiation microwave amplifiers. Owing to its simplicity, the simulation time can be significantly reduced.**

***Keywords*: Electromagnetic interference (EMI), radiated emission, microwave amplifier, microstrip line, printed circuit board (PCB).**

I. Introduction

Fast and accurate estimation of the differential-mode radiation from microstrip lines on printed circuit boards (PCBs), especially at higher frequencies, is important to EMC designers [1]. Proposed methods [1]-[6] first determine the microstrip-line current distribution using the method of moments or the transmission-line theory. Its far-field radiation can be successively calculated by the dipole theory and the free-space Green function [1]-[3], or more accurately, by the dyadic Green function including the dielectric effect [4]-[6]. Compared to the time-expensive full-wave EM simulations, the analytical methods are accurate and time-efficient [7], [8].

The large amount of PCB traces in microwave circuits and systems require fast estimation for their individual and total radiation. This can be achieved by embedding the closed-form radiation expression in the circuit schematic and simulator for EMC/circuit co-simulation [7]. Another modified method is also based on the co-simulation of circuits and electromagnetic interactions [8]. The above methods enable designers to estimate the spurious emission in the design stage; however, research is still lacking on the accurate acceleration of simulation.

In the study, the derived rigorous radiation expression [5], [6] is embedded in a commercial circuit solver for fast simulation, and in order to speed up the process, the expression is further simplified. The simplified expression is obtained by neglecting the phase shift of the electric field resulted from the current position shifted along a microstrip line; nevertheless, the substrate dielectric factor in the dyadic Green function is kept. It is shown that the final simplified expression, written in terms of the line length and its center-point current, is useful in evaluating the radiation for microstrip lines shorter than a quarter wave-length. In addition, it is also valid for longer lines if they are considered as a combination of shorter lines. For the purpose of demonstration, a microwave microstrip amplifier is created and examined. The simulation time of the radiation from this amplifier can be largely reduced from 17 to 6 seconds using the simplified expression embedded in Agilent ADS. In addition, the simulated results are in excellent agreement to the measured results. This nearly three-time efficiency in simulation would be considerable for a much larger microwave circuit or system with numerous traces in practice.

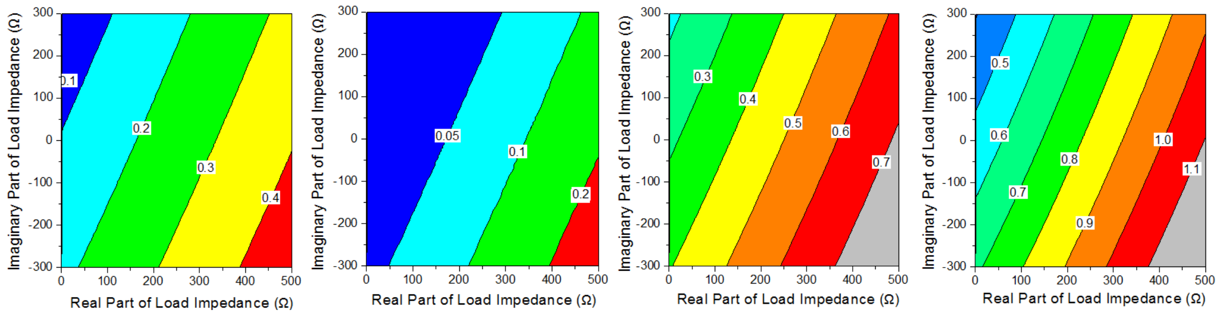
II. Simplified Expression for Microstrip Line Radiation

From [5], [6] the far-field electric field at the standard sphere coordination (θ, ϕ) caused by a x-direction microstrip line can be derived by the dyadic Green function together with the current distribution, expressed as

$$(E_{x\theta}, E_{x\phi})=E_{\mathrm{const}}\cdot(F_{x\theta},F_{x\phi})\cdot\int_0^l I(x)e^{-k_x x}dx \qquad (1)$$

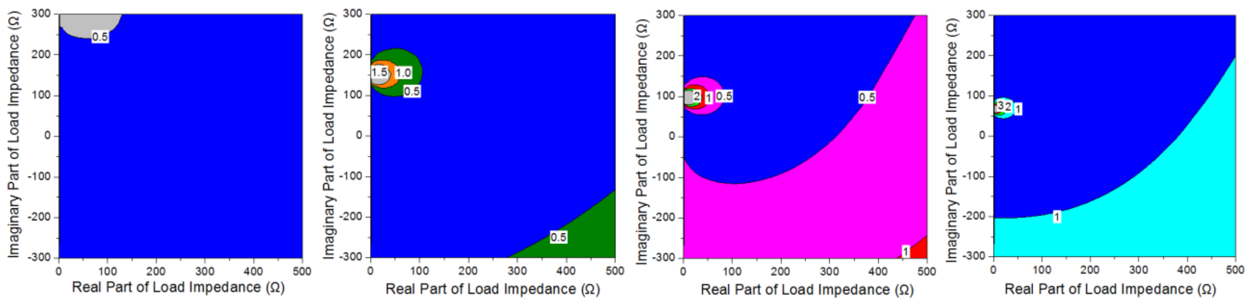
where

$$E_{\mathrm{const}}=\frac{j\omega_0\mu_0}{4\pi}\frac{\mathrm{e}^{-jk_0R}}{R}\,\mathrm{e}^{jk_0(x_1\sin(\theta)\cos(\phi)+y_1\sin(\theta)\sin(\phi))} \qquad (2)$$



(a) (b) (c) (d)

Fig. 1. Deviation (dB) between the simplified and original current-integral expression at $\theta = 0^{\circ}$, for 50-Ω microstrip line with phase delay of (a) 20° (b) 40° (c) 60° (d) 80°.



(a) (b) (c) (d)

Fig. 2. Deviation (dB) between the simplified and original current-integral expression at (θ, ϕ)=(90, 0) for 50-Ω microstrip line with phase delay of (a) 20° (b) 40° (c) 60° (d) 80°.

$$(F_{x\theta}, F_{x\phi})=2jk_0h((\frac{\sin^2(\theta)}{\varepsilon_r}-1)\cos(\phi), \cos(\theta)\sin(\phi)) \quad (3)$$

$$k_x=-k_0\sin(\theta)\cos(\phi)\,. \quad (4)$$

In the above equations, $I(x)$ ($x \in [0,l]$) is the current on a microstrip line with length l, (x_1,y_1) is the leftmost and lowest coordination of the line, h is the substrate height, k_0 is the free space wave number, ε_r is the substrate relative permittivity, and R is the observation distance. The current distribution on a microstrip line can be derived using the transmission-line theory, expressed by

$$I(x)=\frac{I_2(e^{-j\beta_l x}-e^{j\beta_l x})+I_1(e^{-j\beta_l(x-l)}-e^{j\beta_l(x-l)})}{2j\sin(\beta_l l)} \quad (5)$$

where β_l is the phase constant of the microstrip line, I_1=$I(0)$, and I_2=$-I(l)$. The expression for a y-direction microstrip line can be easily obtained by modifying the direction-related parameters in (1)-(5). After substituting (5) into (1), the last term in the RHS of (1) can be simplified as follows:

$$\int_0^l I(x)e^{-k_x x}dx \cong \frac{l^2\beta_l}{2j\sin(\beta_l l)}\,[I_2(-j+\frac{2}{3}k_x l)+I_1(j-\frac{1}{3}k_x l)]$$

$$\cong \frac{-l^2\beta_l}{2\sin(\beta_l l)}(I_2-I_1) \cong lI_H \quad (6)$$

where I_H is the current at the midpoint of the microstrip line with characteristic impedance of Z_0.

The deviations of the simplified expression lI_H from the original current-integral expression $\int_0^l I(x)e^{-k_x x}dx$ in [5] are shown in Figs. 1 and 2 to the load impedance Z_L. Results for 50-Ω microstrip line with different lengths are presented. Fig. 1 is the results at θ=0, showing minor deviation since k_x directly equals to zero at this observation point. However, Fig. 2 shows that when k_x takes its maximum value at (θ, ϕ)=(90, 0), the expression, although still accurate for most of the load impedances, is higher than 3 dB at some Z_L when the phase delay of the microstrip line is about 80°. Fortunately, the load impedances for the simplified expression to be less accurate correspond to lower radiation levels. Finally, the simplified expression of spurious radiation is expressed as

$$(E_\theta, E_\phi)=E_{const}\cdot(F_{x\theta},F_{x\phi})\cdot lI_H\,. \quad (7)$$

On the other hand, since the substrate is very thin compared to the wavelength, the z-direction current I_z can be directly viewed as constant. The radiation from this current can be expressed by

$$E_{\theta z}=E_{const}\cdot F_{z\theta}\cdot I_z \quad (8)$$

where

$$F_{z\theta}=\frac{2h\sin(\theta)}{\varepsilon_r}\ . \qquad (9)$$

To increase the accuracy of the simplified expression (6), a long microstrip line should be separated into two or more shorter parts. Fig. 3 shows the deviation of the simulated electric field (1) using the simplified expression, from that using the original analytical expression. For a half-wavelength microstrip line, the difference is minor when the line is divided by two parts. When the simplified form is employed in simulation, longer microstrip lines should be treated accordingly.

III. Case Study

To validate the simplified expression, the radiation of a single microstrip line and a two-stage microwave amplifier composed of multiple microstrip lines are evaluated using the simplified expression embedded in Agilent ADS, also compared to the measured results. The device under test is 3 m from the receiving antenna, and both the vertical and horizontal electric fields are measured.

(a) Single Microstrip Line

Fig. 4 shows the measured and simulated electric-field intensity, observed at R=3 m and θ=0, for a single microstrip line with ε_r=4.6, h=0.775 mm, w=0.51 mm, and l=10.16 cm. The line is driven by a 1-V source voltage with 50-Ω source impedance, and is shorted at the opposite end. The simulation includes using the original expression and the simplified expression with the microstrip line equally divided from one to three parts. A result drawn from EM simulation [9] is also included for comparison. The original expression is very accurate, and if the microstrip line is considered as two equal-length lines, the result drawn from the simplified expression also agrees with the measurement at all concerned frequencies. In a personal computer with 2.4-GHz CPU, the simulation takes about 2.4 seconds using the original expression in ADS simulation [7] and about 1.8 seconds when the simplified expression is employed with the same accuracy.

(b) Microwave microstrip amplifier

A 1.5-GHz microwave amplifier is fabricated in an FR4 substrate with ε_r=4.6 and h=1.6mm. The schematic and the small-signal gain are shown in Fig. 5. The spurious emission, observed at R=3 m and θ=0, are presented in Fig. 6, together with the simulated results drawn from the original expression and the simplified expression. It is noted that the simulated results drawn from the two expressions are close to the measurement. In a personal computer with 2.4-GHz CPU, the simulation time is 17 seconds using the original

Table I
Mid-point Current (dBμA) / Current Multiplying Length (dBμA・m) of microstrip lines in the amplifier

	1.5 GHz	3.3 GHz		1.5 GHz	3.3 GHz
T_1	67/29	72/**34**	T_{10}	82/41	42/1
T_2	62/24	50/12	T_{11}	75/35	46/6
T_3	66/30	72/**36**	T_{12}	92/**55**	63/26
T_4	73/29	64/20	T_{13}	93/49	60/16
T_5	63/22	61/20	T_{14}	90/**53**	53/16
T_6	66/25	64/23	T_{15}	88/**53**	62/27
T_7	61/24	65/28	T_{16}	91/47	55/11
T_8	80/39	62/21	T_{17}	88/50	56/18
T_9	81/45	27/-9	T_{18}	88/50	62/24

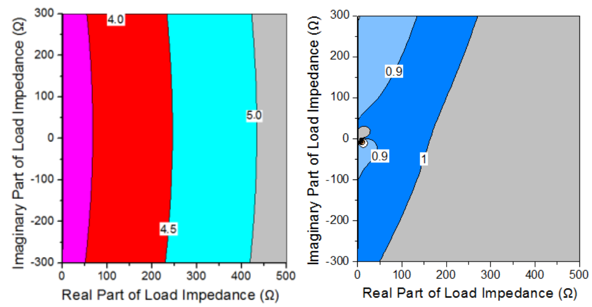


Fig. 3. Difference (in dB) between electric field (R=3m and θ=0) derived from the simplified and the original expression, for a 50-Ω and (a) a 180° line (b) two series 90° microstrip lines.

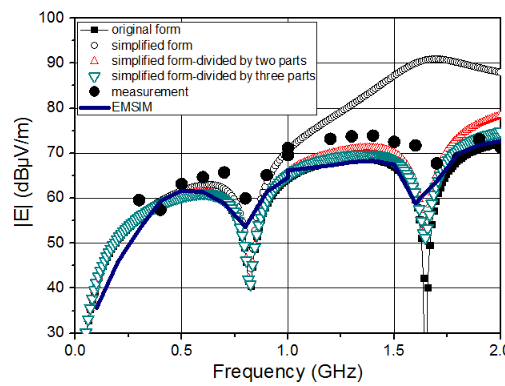


Fig. 4. Measured and simulated results (using EMSIM, original and simplified expressions) for a single microstrip line. (Z_S=50 Ω, Z_L=0 Ω).

expression and can be significantly reduced to 6 seconds using the simplified expression with the same accuracy.

The radiation of the amplifier at its in-band frequency is determined by its output stage, which operates with the highest power in the whole circuit. The simulated radiations from each stage (using both the expressions) are shown in Fig. 7, together with the total radiation. It is demonstrated that the output stage is the most significant source of the undesired radiation at 1.5 GHz; however, at higher frequency, the radiation is determined by the input matching stage since the following stages only attenuate the signal. The mid-point currents I_H and current multiplying length lI_H of all

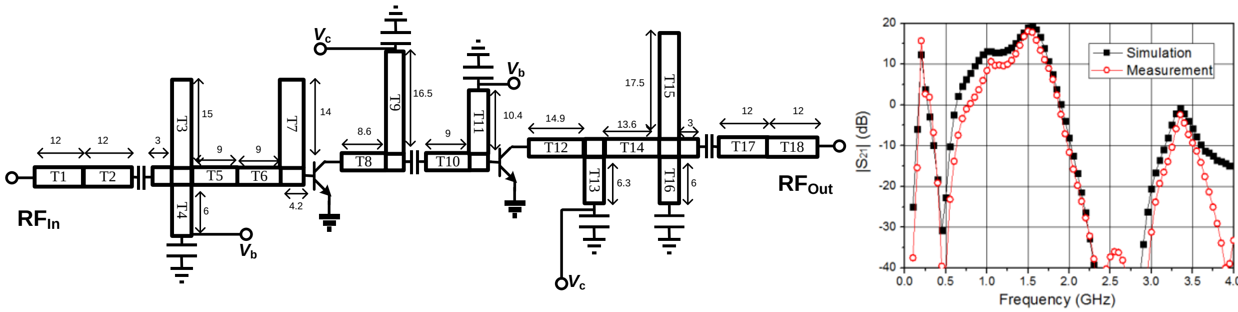


Fig. 5. Schematic (unit in mm) and measured/simulated small-signal gain of the designed 1.5-GHz amplifier.

the microstrip-lines in Fig. 5 are listed in Table I for 1.5 and 3.3 GHz. It is shown that the currents and radiations are higher related to the output stage at 1.5 GHz, while they are higher associated with the input stage at 3.3 GHz. The main contributors of the in-band radiation can be identified to be T12, T14, and T15, while T1 and T3 contribute the most to the radiation at 3.3 GHz.

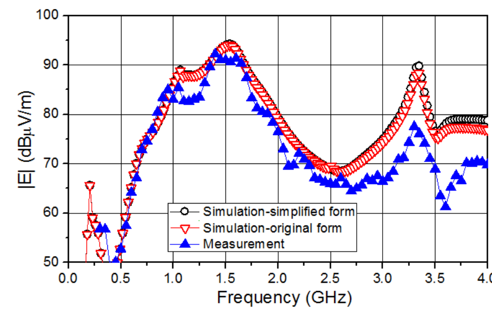


Fig. 6. Measured and simulated amplifier radiation using both expressions. (R=3m, θ=0, -10-dBm input power)

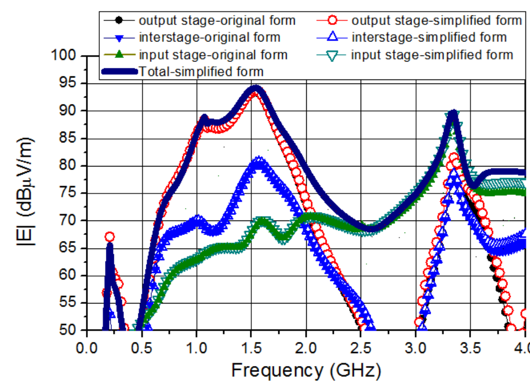


Fig. 7. Simulated total radiation and radiation from each stage of the amplifier. (using both expressions)

IV. Conclusion

In this study, the well-developed and verified closed-form simplified expression of microstrip-line radiation is proposed for fast simulation by commercial circuit solvers. The radiations estimated through the simplified expression are verified by measured results for a single microstrip line. In addition, a multiple-stage amplifier circuit is created and its radiation is simulated by the expression-embedded circuit solver. When evaluating the total radiation of the exemplifying amplifier, the simulation time can be significantly reduced from 17 to 6 seconds with the simplified expression. It is useful and efficient in designing low-radiation microstrip-line networks, especially with large amount of lines.

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