Closed-Form Expressions for the Radiated Emissions from Multiple-Bent Signal Traces on a Printed Circuit Board in Matching Circuits

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1. INTRODUCTION

As the interest in the unintential radiated emission from circuit boards has increased in modern matching circuit design, the reduction of EMI problem and strength to the unwanted spurious signals in modern wireless and portable devices should be considered and required for commercial products [1-4].

In this paper, an analytical study and closed-form expression of unintentional EM radiation from microstrip bent signal traces commonly used in microwave circuits are represented and investigated through several cases using transmission line theory, Thevenin's equivalent theorem, and far-field Green's function expression. The corresponding results estimated from our analysis and developed antenna model are also verified by those from the commercially available software based on Method of Moment (MoM). The effects of the number of corners on the emission level maintaining the total length of matching microstrip line constant can be estimated and predicted by an analytical study with closed form representation and commercially available software. In particular, the far-field radiated emission level has been investigated, verified, and analyzed through the simulated results based on 3-m radiated emission measurement.

2. FIELD REPRESENTATIONS AT ARBITRARY POINTS

Consider the a multiple-bent signal trace which can be modeled as a matching circuit located on a PCB substrate with the given coordinate system as shown in Fig. 1.
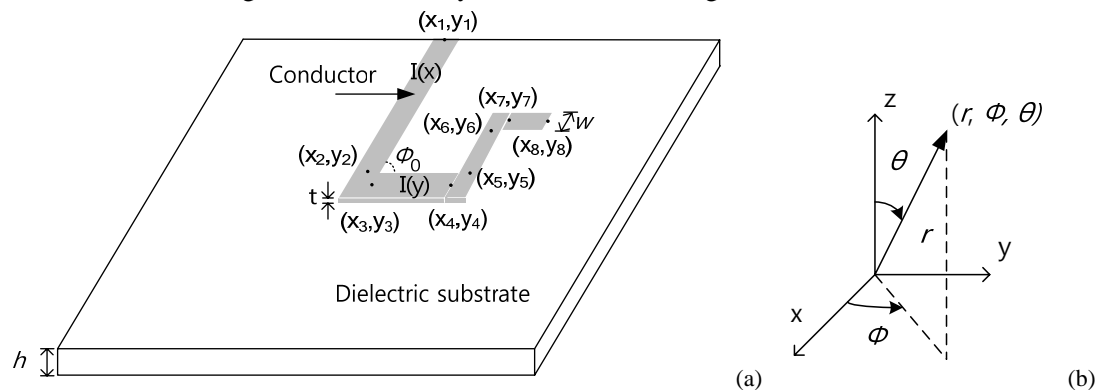

Fig. 1 Multiple-bent signal trace on a PCB substrate with a coordinate system

In order to represent the closed-form electric field radiated from several types of microstrip matching circuits shown with multiple-bent structures in Fig. 1, it is necessary to employ the Green's function representation with a current distribution $\mathbf{I}_s$ on a conducting surface S

$$\mathbf{E(r)} = \int_S \mathbf{I}_s(r^{'})\overline{G}(r,r^{'})dS \tag{1}$$

where $\overline{G}$ is a dyadic Green's function of the given medium. The current distribution $\mathbf{I}_s(\mathbf{r}^{'})$ in Fig. 1 is composed of two types of currents considering horizontal components on the surface and vertical components inside dielectric substrate. The given structure for several matching circuits and the corresponding coordinate system are shown in Fig. 2 and Fig. 1(b), respectively.
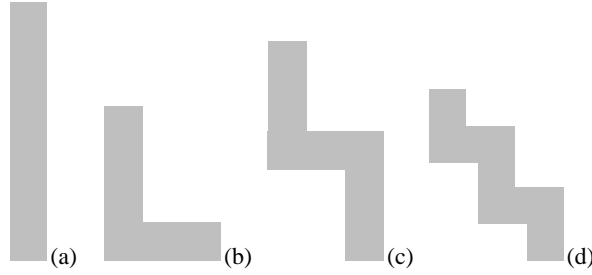

(a)   (b)   (c)   (d)

Fig. 2 Several Multi-bent Signal Traces for Impedance Matching Circuit

The current distributions in $x-$ and $y-$ directions can be represented as follows by using an equivalent circuit shown in Fig. 3, transmission line theory, and Thevenin's equivalent theorem when a single bent signal trace are considered.

$$I(x) = \frac{1 - \Gamma_L^{'}e^{-j2\beta_a l}e^{j2\beta_a x}}{1 - \Gamma_S\Gamma_L^{'}e^{-j2\beta_a l}} \cdot \frac{V_S}{Z_{oa} + Z_S}e^{-j\beta_a x} \tag{2}$$

$$I(y) = \frac{1 - \Gamma_L e^{-j2\beta_b d}e^{j2\beta_b y}}{1 - \Gamma_S^{'}\Gamma_L e^{-j2\beta_b d}} \cdot \frac{V_S^{'}}{Z_{ob} + Z_S^{'}}e^{-j\beta_a x} \tag{3}$$

where

$$\Gamma_L^{'} = \frac{Z_{LL}^{'} - Z_{oa}}{Z_{LL}^{'} + Z_{oa}}, \quad \Gamma_S = \frac{Z_S - Z_{oa}}{Z_S + Z_{oa}}, \quad l = x_2 - x_1$$

$$Z_{LL}^{'} = Z_{ob}^{'} = Z_{ob}\frac{1 + \Gamma_L e^{-j2\beta_b d}}{1 - \Gamma_L e^{-j2\beta_b d}}, \quad d = y_4 - y_3, \quad \Gamma_L = \frac{Z_L - Z_{ob}}{Z_L + Z_{ob}}$$

$$\Gamma_S^{'} = \frac{Z_{LS}^{'} - Z_{ob}}{Z_{LS}^{'} + Z_{ob}} = \frac{Z_S^{'} - Z_{ob}}{Z_S^{'} + Z_{ob}}, \quad Z_{LS}^{'} = Z_{oa}^{'} = Z_{oa}\frac{1 + \Gamma_S e^{-j2\beta_a l}}{1 - \Gamma_S e^{-j2\beta_a l}}$$
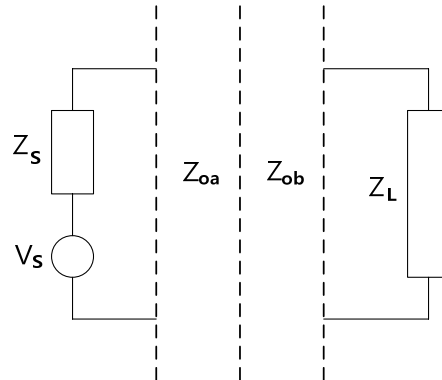

Fig. 3 Equivalent circuit of a bent signal trace in Fig. 2(b)

Hence, the total effective far-field electric field intensity can be written as a summation of two current distributions in x- and y-directions as follows.

$$E_{total}(r) = E_a(r) + E_b(r)$$

where

$$E_a(r) = \sum_{i=1}^{N} \int_{x'=x_i}^{x'=x_i+l} I(x')G_x(r,r')e^{jk_0 r' \cdot \hat{e}_r} dx' \Bigg|_{y'=y_i=y_{i+1}} + \int_{z'=-h}^{z'=0} I(x_1,y_1)G_z(r,r')e^{jk_0 r' \cdot \hat{e}_r} dz' \Bigg|_{x'=x_1, y'=y_1}$$

$$E_b(r) = \sum_{y=1}^{M} \int_{y'=y_j}^{y'=y_j+d} I(y')G_y(r,r')e^{jk_0 r' \cdot \hat{e}_r} dy' \Bigg|_{x'=x_j=x_{j+1}} - \int_{z'=-h}^{z'=0} I(x_M,y_M)G_z(r,r')e^{jk_0 r' \cdot \hat{e}_r} dz' \Bigg|_{x'=x_M, y'=y_M}$$

$$G_i(r,r') = \frac{j\omega\mu_0}{4\pi}\left(\frac{e^{-jk_0 r}}{r}\right)A_i(\theta,\phi), \qquad i = x, \ y, \ \text{and } z.$$

The detailed descriptions for symbol $A_i(\theta,\phi)$ are listed in [1].

3. Simulation and Comparison Results

As a comparison of analysis accuracy, a numerical full-wave computation based on Method-of-Moment (MoM) has been employed with analytical solution. The total length of the straight microstrip line is 10.16 cm. A PCB substrate with permittivity $\varepsilon_r = 4.6$ and thickness $h = 0.775$ mm has been used for simulation. Fig. 4 depicts the frequency response of the electric-field at 3-m distance vertically away from the board. The analytical study and commercial available software employed for a verification is assuming that the ground plane is ideally infinite. The two results of Fig. 4(a) and (b) show a good agreement at the observation angle $\theta = 0$ and $\phi = 0$. As a further example for numerical validation, right-angle bend with a single corner has been calculated from the analytical study and the software FEKO in Fig. 5(a) and (b), respectively. The FEKO simulator used for this work is a 3-D, full-wave, frequency-domain, electromagnetic solver, which is appropriate for the analysis in the radiation problem from signal traces on the PCB. As indicated in Fig. 5, the usefulness of our simple analysis has been validated through a good agreement between two results. All the circuits employed for comparison are excited by a 1V source over the interested frequency range.
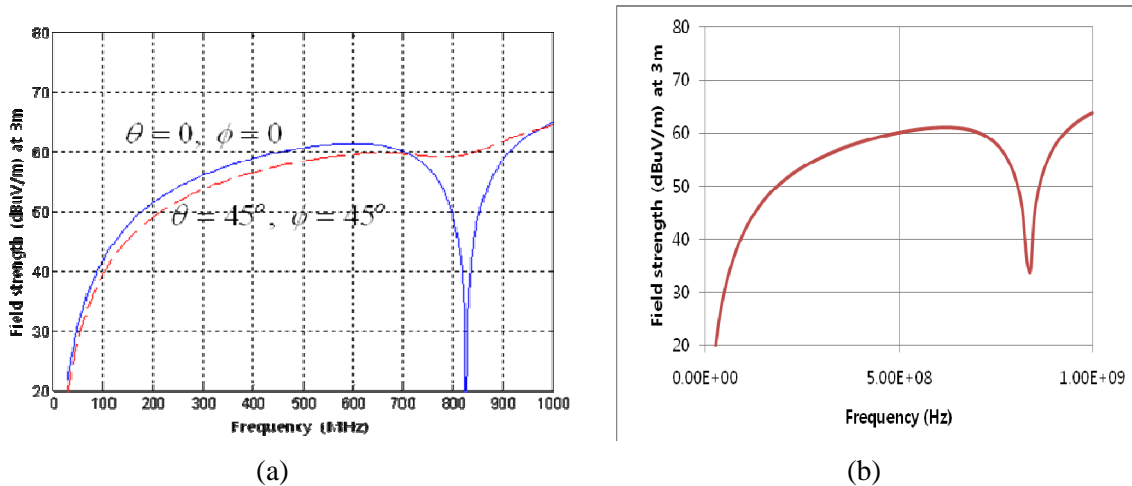

(a)   (b)

Fig. 4 Example for the analytical solution and FEKO simulation result when a straight microstrip line is considered ($Z_L = 0\Omega$, $V_S = 1V$, $Z_S = 50\Omega$, $r = 3m$, $\theta = \phi = 0^o$)
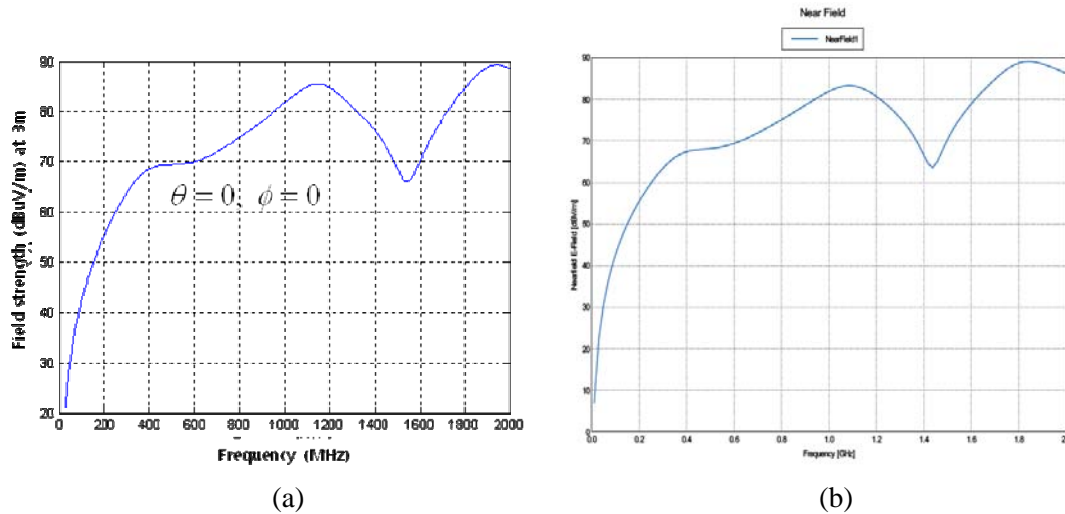
<p align="center">(a)   (b)</p>

Fig. 5 Example for the analytical solution and FEKO simulation result when a right-angle bend is considered

$(V_S = 1V$, $Z_S = 50\Omega$, $Z_L = 0\Omega$, $r = 3m$, $\theta = \phi = 0^o$, $\varepsilon_r = 4.6$, $h = 1mm$, $w = 5mm$, $x_2 - x_1 = 5cm$, $y_2 - y_1 = 5cm$, $\phi_0 = \pi / 2$)

4. CONCLUSION

In this article, mathematically closed-form representations with a commercially available software has been introduced and investigated by considering the radiated emissions from a PCB substrate with several matching circuits necessary to design low-loss active circuits. In addition, in order to analyze the effects of the number of corners on the radiation level, it is shown that the PCB substrate with several bend structure could be modeled as transmission lines and Thevenin's equivalent circuits with Green's function formulations. From the analytical study, it is shown that the contributions of the radiated emission from each bend structure can be divided into contributing factors affecting mainly the total radiated emissions.

REFERENCES

[1] H.-C. Hsieh et al., "A new approach for fast analysis of spurious emissions from RF/Microwave circuits," *IEEE Trans. On EMC*, vol. 51, no. 3, pp.631-638, Aug. 2009.

[2] M. Leone, "Closed-form expressions for the electromagnetic radiation of microstrip signal traces," *IEEE Trans. On EMC*, vol. 49, no. 2, pp. 322-328, May 2007.

[3] B.-C. Tseng et al., "Analytical solutions for the radiated emission of parallel microstrip traces," *IEEE Trans. On EMC*, vol. 53, no. 3, pp. 842-845, Aug. 2011

[4] D.-Y. Kim et al., "Indirect evaluation of radiated emissions from a bent signal line on a printed circuit board with two attached cables," *Microwave and Optical Technology Letters*, vol. 53, no. 8, pp. 1832-1837, Aug. 2011