Suppression of Mode-Conversion by DNG Material for Differential-Paired Lines with Bend Discontinuities

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Abstract
This paper newly attempts to propose a method for compensating the mode-conversion by double negative (DNG) material for suppression of imbalance (common-mode) component and EMI generated by differential-paired lines with bend discontinuities, without the deterioration of the SI performance. The concept is based on compensation of phase-difference due to the bend discontinuities, by using DNG material with phase-constant \( \beta = 0 \) at a certain frequency. When the DNG material is located on discontinuity region asymmetrically, it was evaluated that CM component and the simulated \( |S_{d21}| \), which is defined as the conversion from differential-mode (DM) to CM, can be compensated. The significant suppression effectiveness of \( |S_{d21}| \) in the case study is achieved by 13 dB around target frequency (100 MHz) using DNG material. Although DNG characteristics has not been established by real transmission line structure, the results validate the proof of concept and that proposed method should be one of the potential candidates of a basic method for suppressing mode-conversion due to phase-difference.

Keywords: Differential-paired Lines, Bend, Signal Integrity, Electromagnetic Interference, Differential-mode, Common-mode, Double Negative (DNG) Material

1. Introduction
Differential-signaling techniques such as low-voltage differential-signaling (LVDS) are widely used to establish a high-speed digital propagation with low-electromagnetic interference (EMI).[1] But there are the non-ideal symmetrical topologies due different length and bend discontinuities in actual differential-paired lines, and hence the ideal balanced differential-signaling cannot be established. Hence, unintentional imbalance components are generated in voltages traveling the differential paired lines and they deteriorate signal integrity (SI) and intensify EMI.

Many papers have contributed to suppress imbalance component (common-mode: CM) in differential-signals, due to a bend region and asymmetrical layouts, by the proposed layouts for compensation.[2–10] The taper bend discontinuities and meander delay line as equi-distance routing technique have been proposed to improve and compensate SI performance. But the previous researches have mainly focused on SI issue. Therefore fundamental study for predicting and suppressing EMI as well as establishment of signal integrity over a broad band are both required.

Some previous paper written by the authors[11–13] have discussed the correlation between the conversion parameter from balance component (differential-mode: DM) to CM, \( |S_{d21}| \) and EM from asymmetrical differential-paired lines. Although equi-distance routing is suitable for the improvement of SI issues, it does not work well for the suppression of the far-field potential radiation. For resolving EMI problems underlying differential-paired lines, expected design guideline for differential-paired lines routing is to place to equi-routing near the phase-difference region whenever possible. In preparation for the expected design guideline, the compensation capacitance has been proposed.[3, 5] Both models in the literatures adequately compensate imbalance component and far-end crosstalk. An effective and practical method for implementation is preferred. Locally shielded differential-paired lines with turnoff point for SI and EMI performances has been proposed for providing the practical design and implementation methodologies.[14]

Alternatively, new method and/or material structure are
expected to develop in near future for the suppression and filtering to the EMC problems. The application of the metamaterial and/or the left hand (LH) mode medium, which has simultaneously negative permittivity and permeability (double negative: DNG) and represents negative refractive index should be investigated for the near future solution of the EMC problems.[15–17] Negative group delay is one of the anomalous characteristics of the metamaterial, and can be used to compensate the group delay. Furthermore, DNG material constructed by composite right-and left handed transmission-line (CRLH-TL) has wideband dispersion characteristics and phase-constant $\beta = 0$ at a certain frequency. So far, the authors have proposed the embedded Folded-Steped Impedance Resonator (F-SIR) structure with compact open-stub resonator to establish a method for designing negative group delay and slope characteristics.[18–20] Although DNG characteristics with $\beta = 0$ has not been established by real transmission line structure constructed by F-SIR yet, its application and capability to solve EMC problems should be studied.

This paper newly attempts to propose a concept of method for compensating the mode-conversion by DNG material for suppression of imbalance component and EMI generated by differential-paired lines with bend discontinuities, without the deterioration of the SI performance. The concept is based on compensation of phase-difference due to the bend discontinuities, by using DNG material with $\beta = 0$. Although DNG characteristics with $\beta = 0$ has not been established by real transmission line structure by F-SIR yet, this paper focus on a proposal and proof of the basic concept. Firstly, the basic concepts and modeling method are described with the simple differential-paired lines with different length in Section 2. In section 3, mixed-mode scattering parameters for the “different length” case are studied by numerical modeling based on FDTD method. Then, the imbalance component on the differential-paired lines, which is the key of the total SI/EMI behavior of the PCB, is discussed. The case for “differential-paired lines with bend” is discussed in Section 4. Section 5 is conclusions.

2. Compensation by DNG Material

2.1 Model case and basic concept

For the explanation of basic concept of compensation by DNG material, the differential-paired lines with different length were used as a basic model. As appropriate and simple model for studying and getting physical-insights, the geometries and cross-sectional view of the PCBs under study are illustrated in Fig. 1. The size of the microstrip line structure used for the test model is 120 mm of length, 100 mm of width, and $h = 1.53$ mm (thickness) for the dielectric substrate with a relative permittivity of $\varepsilon_r = 1.0$. Air is chosen as the dielectric substrate in the basic model because of followings reasons: easy calculations of phase-velocity and phase-constant, and identical relative dielectric constant for DM and CM. Relatively wide separation of $s = 1.0$ mm is selected. A symmetrical differential-paired lines has the differential mode impedance $Z_{DM} = 100$ $\Omega$. Length of Line 1 ($l_1 = 100$ mm) is longer than that of Line 2 ($l_2 = 95$ mm) and hence the difference of geometrical length between Line 1 and 2 is 5.0 mm. The dominant factor for generation of imbalance component of the model under study is difference of the geometrical length between Line 1 and Line 2.

Figure 1(b) shows the cross-sectional view of the differential-paired lines without DNG material. The PCB has cross sectional three layers, with the upper layer for the signal trace, middle layer for the dielectric substrate (Air) and the lower layer for the reference (ground) plane.

For simple understanding of basic concept, the wide-separation case is assumed, where the far-end cross-talk $S_{41}$ and $S_{23}$ can be neglected in generation of imbalance
component. Furthermore, lossless transmission line with attenuation constant $\alpha = 0$ is also assumed.

Based on the transmission line theory, the imbalanced current at the ends of the differential paired lines without DNG material can be calculated by the following:[12, 14]

$$I_{imb} = I_{DM}(e^{-j\beta l_1} - e^{-j\beta l_2})$$

(1)

where $I_{DM}$ is the magnitude of the differential-mode current and $\beta_1$ and $\beta_2$ are the phase constant which is calculated by an assumption of single-ended transmission. This paper distinguishes $\beta_1$ and $\beta_2$ for the simple understanding of the potential method for compensation of phase-difference.

Under the condition of model PCB shown in Fig. 1,

$$\beta_1l_1 > \beta_2l_2.$$ 

(2)

There are three possible means for compensation of imbalance:
1) The difference of geometrical length between Length $l_2$ of Line 2 and length $l_1$ of Line 1 are compensated.

This is conventional method such as meander delay line and equi-distance routing.
2) Equivalent phase constant of Line 2, $\beta_2$, is increased.

The compensation capacitance, stub and locally shielded structure are classified to this approach 2).
3) Equivalent phase constant of Line 1, $\beta_1$, is decreased.

The DNG characteristics and negative group delay are classified to this approach 3). This paper focuses on this approach 3).

The concept is based on compensation of phase-difference due to the bend discontinuities, by using DNG material with $\beta = 0$.

The DNG material is placed on discontinuity region asymmetrically as shown in Figs. 1 and 1(c). Line 1 with longer geometrical length is embedded by DNG material. Negative effective relative dielectric constant is expected, and it is lower than that of micro-stripline structure (no-DNG material $\varepsilon_r = 1.0$). And hence, the propagation velocity in the region of locally shield layout is faster than in the region of micro-stripline structure (no-DNG material).

Consequently, the locally covered layout on Line 1 with longer geometrical length can compensate the imbalance component due to the phase-difference, by setting appropriate size (region) of DNG material.

In the “different length” with DNG material case shown in Fig. 1, the imbalance component current is expressed:

$$I_{imb} = I_{DM}(e^{-j(\beta_1 l_1 + \beta_2 l_2)} - e^{-j\beta_1 l_1}),$$

(3)

where $\beta$ and $\beta'$ are the phase constant in the region of the “Air” and “DNG”.

For the perfect balanced case,

$$\beta_1 l_1 + \beta_2 l_2 + \beta_1 l_1 = \beta_2 l_2,$$

(4)

where $l_1 = l_1 + l_1 + l_1$. Since the phase-constant depends on the cross-sectional view, it is easy to satisfy the condition for the perfect balanced case by changing the length $l_{1b}$.

The condition for the perfect balanced case is derived:

$$l_1 = \frac{\beta}{\beta - \beta'}(l_1 - l_2)$$

(5)

From $\beta = \frac{2\pi}{\lambda} = \frac{2\pi f \text{Re}(n)}{c_0}$, the expression:

$$l_1 = \frac{\text{Re}(n)}{\text{Re}(n) - \text{Re}(n')}(l_1 - l_2),$$

(6)

where the $n$ and $n'$ are effective real part of refractive index for the “without DNG” and “with DNG” case, respectively.

For Re($n$) > Re($n'$), positive $l_{1b}$ are obtained and then the compensation by DNG material can be achieved. In the Re($n'$) = 0 at which the phase velocity is infinity, $l_{1b} = 5\text{ mm}$ identical to difference of geometrical length. The expression mentioned above is a rough estimation because there are some assumption for easy explanation and estimation. Nevertheless, from viewpoint of demonstration of the validity of the basic concept, calculations are performed.

### 2.2 FDTD modeling of DNG material

The FDTD (Finite-Difference Time-Domain) modeling is used to calculate the mixed-mode scattering parameters. The DNG material is modeled by Debye-Drude model:[21, 22]

$$\varepsilon_r(\omega) = \varepsilon_\infty + \left(\frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\sigma_0}\right) + \frac{\sigma}{j\omega\varepsilon_0}$$

(7)

$$\mu_r(\omega) = \mu_\infty + \left(\mu_s - \mu_\infty\right)\frac{1}{1 + j\omega\mu_0} + \frac{\sigma_m}{j\omega\mu_0}$$

(8)

where $\varepsilon_s$ and $\mu_s$ are the static relative permittivity and permeability, $\varepsilon_\infty$ and $\mu_\infty$ are the infinite frequency relative permittivity and permeability, and $t_\sigma$ and $t_\mu$ are relaxation time for permittivity and permeability, $\sigma$ is the electric conductivity, and $\sigma_m$ is the magnetic conductivity. The refractive index $n$ is defined:

$$n(\omega) = \sqrt{\mu_r(\omega)\varepsilon_r(\omega)}$$

(9)

EM wave cannot propagate through a material with imaginary refractive index. A negative sign for the square root must be chosen when both relative permittivity and permeability are negative. The limitation should be satisfied
to achieve double negative condition;

\[
\sigma \geq \frac{\epsilon_0 (\epsilon_s - \epsilon_m)}{t_{r0}} \quad (10)
\]

\[
\sigma_m \geq \frac{\mu_0 (\mu_s - \mu_m)}{t_{m0}} \quad (11)
\]

Although a target frequency is quite arbitrary, 100 MHz and 1000 MHz are chosen as one specific frequency in the practical frequency range (several hundred Megahertz to a few Gigahertz). The proposal concept and the design guidelines (Eq. (6)) is independent of the value of the target frequency. Consequently, the parameters in this study are selected so that real part of \( n \) is \(-1\) at 100 MHz, and hence the real part of \( n \) is 0 at 100 MHz; i.e. static relative permittivity and permeability \( \epsilon_s = \mu_s = -79.9 \), infinite frequency relative permittivity and permeability \( \epsilon_m = \mu_m = 1 \), relaxation time \( t_{r0} = t_{m0} = 10 \) ns, electric conductivity \( \sigma = 0.07 \) S/m, and magnetic conductivity \( \sigma_m = 1.02 \times 10^4 \) Ω/m.

Figure 2 shows the frequency response of real part of refractive index \( n \). The real part of \( n \) at 100 MHz and 1000 MHz are \(-1\) and 0, respectively. Based on the proposed concept, the discussion on suppression effectiveness should be focused on around the target frequency (100 MHz–141 MHz).

3. Validation of Proposed Concept

To demonstrate the validity of the proposed concept, the frequency response of mixed-mode scattering parameters are studied. The simulated frequency response mixed-mode scattering parameters with different DNG length \( l_1 \) are shown in Fig. 3. \( l_1 \) is varied from 0(without) to 15 mm, while \( l_2 = 50 \) mm constant. Figure 3(a) shows \(|S_{dd21}|\), which is defined as the transmission coefficient of the differential-mode. \(|S_{dd21}|\) below 50 MHz is slightly deteriorated. 50 MHz is lower than our target frequency (around 100 MHz). In the frequency range, over-compensation is occurred and hence DM component is converted to CM component. But there is no remarkable difference of results of the “with” and “without” cases above 50 MHz. This shows there is no deterioration of transmission characteristics due to the DNG material at around the target frequency.

Figure 3(b) shows the frequency response of \(|S_{cd21}|\), which is defined as the conversion from DM to CM. In the “without DNG” case, the frequency response of imbalance component \(|S_{cd21}|\) up to 6 GHz follows 6 dB/octave (20 dB/decade). In the “with DNG material” case, the significant suppression effectiveness of \(|S_{cd21}|\) in the case study is achieved around the target frequency by DNG material. As \( l_1 \) becomes longer, anti-resonance frequency identical to maximum effective frequency becomes higher.

Figure 4 shows the relationship \( S_{dd21} \) at 141 MHz with different \( l_1 \). The best condition with the smallest \( S_{dd21} \) for the FDTD simulation is \( l_1 = 7.25 \) mm. There is slight dif-
ference from the $l_b = 5.0$ mm obtained from Eq. (6). The establishment of design methodology for the appropriate condition should be one of the further studies.

As the discussions here are limited for differential paired lines with wide separation, the acquired knowledge are able to apply to practical implementation. Consequently, the validation of the proposed method is demonstrated for the basic model.

4. Demonstration of Compensation for the “Differential Paired Lines with Bend” Case

4.1 PCB under study

Differential-paired lines with discontinuities at turnoff point (so called bend) were prepared as typical routing. The geometries and cross-sectional view of the PCBs under study are illustrated in Fig. 5. For comparison, the geometry is identical to our previous model.[14] The size of the microstrip line structure used for the test model is 100 mm of length, 100 mm of width, and $h = 1.53$ mm (thickness) for the dielectric substrate with a relative permittivity of $\varepsilon_r = 4.5$. The relatively wide separation $s = 1.0$ mm is selected. A symmetrical differential-paired lines has the differential mode impedance $Z_{DM} = 100 \, \Omega$. Length of Line 1 ($l_1 = 102.9$ mm) is longer than that of Line 2 ($l_2 = 97.1$ mm) because of the bend. The difference of geometrical length between Line 1 and 2 is 5.8 mm. In the equivalent circuit expression, the different length of 5.8 mm is equivalent to additional inductance of 2.1 nH and additional capacitance of 0.6 pF.[14]

4.2 Results and discussion

To demonstrate the impact of the DNG material on CM component, the frequency response of mixed-mode scattering parameters are studied. The frequency response mixed-mode scattering parameters are shown in Fig. 6.
Figure 6(a) shows $|S_{dd21}|$. The solid and broken lines show the measured results in the “without DNG” case and the calculated results by FDTD method, respectively. The measured and calculated results are in good agreement. The deterioration of $|S_{dd21}|$ above 5 GHz is resulted from a dielectric loss of FR-4 material. There is no remarkable difference of results of the “with” and “without” cases at around the target frequency. This shows there is no deterioration of transmission characteristics due to the DNG material.

Figure 6(b) shows the frequency response of $|S_{cd21}|$. The significant suppression effectiveness of $|S_{cd21}|$ in the case study is achieved around the target frequency by DNG material. The suppression effectiveness at 100 MHz is 13 dB. It is estimated that the proposed structure is suitable for suppressing the CM in the case study, without the deterioration of the transmission coefficient around the target frequency.

5. Conclusion

This study reported that the DNG with $\beta = 0$ should be one of the potential candidates of a basic method for suppressing imbalance component of differential-paired lines with bend discontinuities. Although DNG characteristics is modeled as numerical simulation and has not been established by real transmission line structure by F-SIR yet, the simulated results by FDTD modeling validate the proof of concept. The proposed method is good candidate for suppressing mode-conversion due to phase-difference. Though proposed method still has some limitation of frequency characteristics on the constant value of $l_b$ and the target frequency, continuous research work will make a progress for suppressing mode-conversion due to phase-difference.

The establishment of design and achievement methodologies for the appropriate DNG characteristics by F-SIR should also be one of the further studies for the real implementations.

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