Left-Handed Transmission Line Characteristics Made by F-SIR Structure on PCB

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Abstract—Basic left-handed transmission line (LH-TL) characteristics made on PCB is an important future issue for the application of the EMC field. In this paper, possibility of a LH-TL characteristic made by a folded-stepped impedance resonator (F-SIR) type is investigated experimentally and theoretically as a first time. The calculations by FDTD and/or FEM (HFSS) show the usability of the LH-TL. The experimental results indicate some back-ward propagation characteristic but the differences with the calculation is still existed.

Key words: Left-handed transmission line, printed circuit board, folded-stepped impedance resonator, back-ward propagation

I. INTRODUCTION

Recent electronics systems which are essential to information technology society are getting smaller and operating in very close to each other. Near field problem not only far-field issue is very important factor for the mutual interference, so called intra-EMC problem. Ultimate problems may exist in the IC itself. Alternatively, new method and/or material structure are wanted to see in near future for the suppression and filtering to the EMC problem. The application of the meta-material and/or the left-handed (LH) medium, which has equivalently negative permittivity and permeability and refractive index, should be investigated for the near future solution of the EMC problem [1].

As an expression of the equivalent circuit is shown as ladder circuit of capacitance and inductance and can be treated in the transmission theory, new applications for microwave circuits which have left-handed transmission line (LH-TL) and peculiar electromagnetic (EM) responses have been proposed [2]-[7]. Therefore, it is also expectable if LH-TL structure does not exist. One of the structures having the LH characteristics is composite right/left-handed transmission line (CRLH-TL) [3]. CRLH-TL is consisted of right-handed and left-handed transmission lines as shown in Fig. 1(b). At lower frequencies, CRLH-TL corresponds to purely LH-TL. To construct a CRLH-TL on microstrip line, it is necessary series capacitor and a shunt inductor in the transmission line representation. So far, CRLH-TL is implemented in inter-digital capacitor and stub inductor on microstrip line structure. This method requires shorted via. Since such via becomes a serious problem in the fabrication process, the CRLH-TL without via has been proposed by using conductor-backed coplanar strips [8].

On the other hand, folded-stepped impedance resonator (F-SIR) structure has some advantages in microwave filter [9], [10].Key features of SIR are as follows:

1. A wide degree of freedom in structure and design
2. A wide range of applicable frequency through the use of various types of transmission line
3. Possibility of down sizing
4. Low loss
5. Easier design by changing length and width of the resonator

So the SIR can be applied not only to filters but also to LH-TL. Consequently, conductor-backed F-SIR structure, as shown in Fig. 2(a), is chosen as transmission line implementation. Figure 2(b) shows equivalent circuit model for periodic F-SIR.
The gap between F-SIR and input/output lines is expressed as series capacitor. The gap between F-SIRs is also expressed as series capacitor. The F-SIR is expressed as $RLC$-parallel resonant circuit, where the shunt resistance $R_p$ is disregarded in this paper. At lower frequencies (below parallel resonant frequency), F-SIR is behaved as shunt inductor. Hence LH characteristics are achieved by periodic F-SIR structure.

![Periodic F-SIR](image1)

![Equivalent circuit model for periodic F-SIR](image2)

**Fig. 2 F-SIR Structure.**

B. **Model for the Discussion**

Figure 3 shows F-SIR model under test. (a) is the layout, (b) and (c) are photograph. The PCB consisted of conductor backed coplanar strip line. The PCB has two layers, with the upper layer for the signal and ground traces and the lower layer for the reference (ground) plane. The size of PCB is 114mm length, 90mm width, and 1.53mm thickness of the dielectric substrate with a permittivity of $\varepsilon_r=4.5$. The trace, with 2.0mm width, is located on the dielectric substrate. The distance of gap between the F-SIR and the input/output lines is 2.0mm.

### III. EXPERIMENTAL AND MODELING METHODS

A. **Experimental Method**

The experimental method, usually used for transmission line on the printed circuit board, is applied to the developed samples. The transmission coefficient (magnitude $|S_{21}|$ and phase $\angle S_{21}$) was measured using a network analyzer (Agilent E8358A). The network analyzer is calibrated on the tip of the connector. The measured frequency range was from 300kHz to 9GHz.

At general measurement for Scattering-parameters, ends of the transmission lines should be terminated with its characteristic impedance. Although the ends of lines are connected to 50$\Omega$ port, 50$\Omega$ is not matched to the characteristic impedance of the transmission line. However, it is considered that the estimation of the transmission characteristic is possible.

A dispersion diagram is plotted using Eq. (1). A group delay $\tau_g$ is calculated by using Eq. (2).

\[
\beta d = -\angle S_{21}
\]

\[
\tau_g = -\frac{\partial \phi}{\partial \omega} = -\frac{1}{2\pi} \frac{d\angle S_{21}(f)}{df}
\]

B. **Numerical Modeling**

Two numerical methods are used for numerical analysis. One method is finite-difference time-domain (FDTD) method. An analytical space was composed from non-uniform size of the cells. The size of cells in coarse region are $\Delta x=0.2$, $\Delta y=2.0$, $\Delta z=2.0$mm and that in fine region near the signal trace and dielectric substance is $\Delta x=0.2$, $\Delta y=0.2$, $\Delta z=0.51$mm, respectively. PML of 12 layers was used for the absorbing boundary condition. The metal is modelled as a perfect electric conductor without thickness.

Other method is finite element method (FEM). In this paper, commercial software (ANSOFT, HFSS) is used for FEM calculation.

### IV. RESULTS AND DISCUSSION

A. **Measurement and Field Simulation**

Frequency response of transmission coefficient $|S_{21}|$ is shown in Fig. 4. The solid, broken and chain lines indicate measured, FDTD and FEM calculated results, respectively. Result indicates that F-SIR structure has the narrow LH pass-
band at around 0.9GHz (Measured: 900MHz, FDTD: 788MHz and FEM: 857MHz) and also right-handed pass-band around 3.4GHz. These results indicate that F-SIR structure can construct CRLH-TL. Measured result on frequency response is approximately similar to those of FDTD and FEM calculated results. However, measured result $|S_{21}|$ at LH pass-band is -30dB and is smaller than that of numerical modeling. This difference may result from losses of dielectric and metal.

Figure 5 shows dispersion diagram. Measured result shows negative phase-constant below 0.9GHz. This indicates that proposed transmission line made by F-SIR structure on PCB has LH characteristic with back-ward propagation. In addition, measured result in frequency range between 734 - 802MHz shows negative-slope which means negative group delay (velocity).

Frequency response of group delay $\tau_g$ is shown in Fig. 6. It is demonstrated that negative group delay in frequency range between 734 - 802MHz is achieved. On the other hand, there is no negative group delay characteristic in FDTD calculated result.

B. Circuit Approach

Equivalent circuit model provides enough flexibility to different geometric parameters, and increases the ability to provide insight and design guidelines. By using the equivalent circuit model, we attempt to demonstrate the validity of LH characteristics made by F-SIR structure on PCB.

An equivalent circuit model for F-SIR type transmission lines is used for calculation of the transmission characteristic and dispersion diagram. Figure 7 shows the equivalent circuit model. The equivalent circuit consists of five parts: a source, a transmission line based on the TEM assumption, electric coupling due to the gap, LC-parallel resonant circuit due to the F-SIR, and a termination (load). The capacitances ($C_s$, $C_p$, $C_{g}$ and $C_{r}$) of circuit parameters are calculated by 3D-field solver (ANSOFT, Maxwell Q3D Extractor). On the other hand, the inductances ($L_L$ and $L_R$) are calculated by cut-off frequency [3] of 900MHz and 3.4GHz, respectively.

Frequency response of $|S_{21}|$ is obtained from the equivalent circuit model using H-SPICE. Calculated $|S_{21}|$ and dispersion diagram are shown in Figs. 8 and 9, respectively. The measured and calculated results on equivalent circuit model 2 are in good agreement up to 2GHz. The model 2 has an anti-resonance at 700MHz. So capacitance $C_p$ is important element.
Fig. 8 Frequency response of transmission coefficient $|S_{21}|$.  

![Graph showing frequency response of transmission coefficient](image1)

Fig. 9 Dispersion diagram.  

![Dispersion diagram](image2)

Fig. 10 Dispersion diagram obtained from $ABCD$-matrix (frequency range between 0.85-0.95 GHz).

The equivalent circuit model 2 is used to calculate $ABCD$-matrix ($F$-parameter). The dispersion diagram is calculated from acquired $ABCD$-matrix and Eq. (3) and (4), and is shown in Fig. 10. 

$$S_{21} = \frac{2}{A + B / Z_0 + CZ_0 + D} \quad (3)$$

$$\beta d = \cos^{-1} \frac{A + D}{2} \quad (4)$$

Result indicates that F-SIR structure has LH characteristic in frequency range between 0.878-0.890GHz, i.e., LH passbandwidth is 12MHz. Consequently, validity of LH-TL characteristics is demonstrated.

V. CONCLUSION

The possibility of a LH-TL characteristic made by the F-SIR type was investigated experimentally, numerically and theoretically. The calculations by FDTD and/or FEM (HFSS) show the usability of the LH-TL. The experimental results indicate some backward propagation characteristic but the differences with the calculation is still existed.

The high-Q and wideband LH pass band is required to solve the practical EMC problem. Further work will be carried out on this concept.

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