MICROWAVE DIRECTIONAL FILTERS USING METAMATERIAL CLOSED-LOOP RESONATORS

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ABSTRACT: *The design and construction of two Metamaterial (MTM) directional filters (DF) for multiplexing applications at 900 MHz is presented. The four-port filters are realized using composite-right-left-handed (CRLH) closed-loop resonators, which present small dimensions and suppression of harmonic resonances due to the zeroth-order resonance produced by MTM's. The first filter uses two conventional transmission lines (TL) between resonators to generate the necessary constructive-destructive interference for directional behavior. The second design is further miniaturized by a CRLH TL. The simulated responses are compared with measured data showing good agreement.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 1155–1156, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24275

Key words: *metamaterials; directional filter (DF); closed-loop resonators*

1. INTRODUCTION

Speculations of materials with simultaneously negative permittivity ε and permeability μ coefficients were made by the Russian physicist Viktor Veselago in 1967 [1]. Artificial structures with such properties were named left-handed metamaterials (LH MTM), because of the reversal effects that they produce compared with conventional (Right Handed-RH) materials. In practical MTM circuits, conventional RH properties appear at higher frequencies as a consequence of parasitic effects, so a pure LH medium does not exist. This was the motivation for the term composite-right-left-handed (CRLH) structures [2]. When CRLH TL's are used as resonators, device miniaturization and suppression of harmonic resonances are possible [2, 3]. One characteristic of CRLH lines is the possibility of obtaining 0° phase shifts by phase cancellation of the LH and RH parts [4]. If such line is looped then 0° phase shift loop resonators can be implemented with much smaller dimensions compared with conventional $\lambda_g/2$ and ring resonators [5].

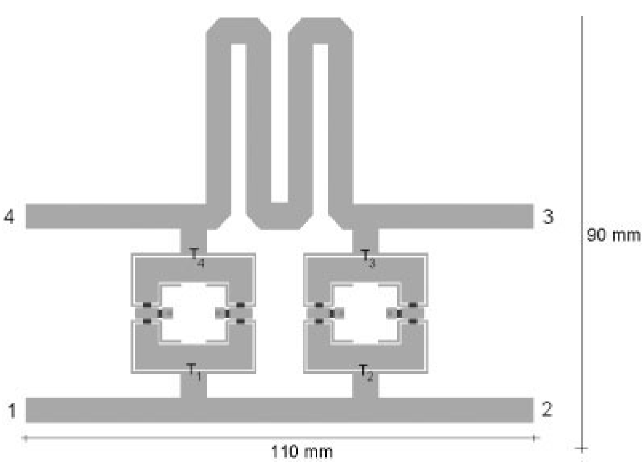

Figure 1 MTM directional filter

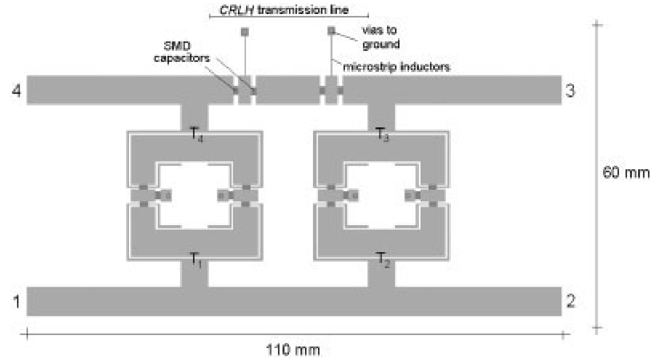

Figure 2 Miniaturized MTM directional filter

One of the most common uses of microwave filters is in frequency multiplexing. For this application, directional filters (DF) are ideal candidates as they can be cascaded in series to form the multiplexing network. A DF is a four-port device having a bandpass response in port 4 (S_{41}) with the complementary reject-band response in port 2 (S_{21}). For a perfectly matched circuit, no power is transmitted to port 3 and none is reflected to port 1. The principle of operation in DF's is the constructive-destructive interference effect [6].

In this article, the use of closed-loop MTM resonators and TL's for the design of directional filters for multiplexing applications is presented resulting in device miniaturization and no-harmonic generation. The design procedure with simulations and experimental results are exhibited.

2. MICROWAVE DIRECTIONAL FILTER DESIGN

A CRLH TL can be formed by cascading a conventional RH TL and symmetrical LH cells. In a LH cell, the phase gives a positive phase shift, whereas in conventional RH TL's the phase lags in the direction of the group velocity incurring in a negative phase shift [4]. The total phase shift of a cascaded RH-LH combination (Φ_{CRLH}) can be calculated [5] using Eq. (1):

$$\Phi_{CRLH} = \Phi_{RH} + \Phi_{LH} = (-2\pi f l_{MS}(\varepsilon_{eff})^{1/2})/c + N/(2\pi f(L_L C_L)^{1/2}) \tag{1}$$

where Φ_{LH} and Φ_{RH} are the LH and RH phase shift respectively, N is the number of LH cells, ε_{eff} is the substrate effective permittivity coefficient, l_{MS} is the length of the microstrip line, and f is the frequency of evaluation. L_L and C_L are the LH inductor and capacitor values respectively.

A LH unit cell was designed to give a phase shift of +50° and then cascaded with a conventional RH TL with a phase shift of −50°. To form a resonator, two of these unit CRLH cells were cascaded and looped together achieving a zero phase shift along its overall circumference at the frequency of operation. The resonator was designed at 900 MHz using Rogers 5880 DUROID substrate, with $\varepsilon_r = 2.2$ and thickness $h = 1.575$ mm. The capacitances and inductances were implemented using lumped element SMD's of values 8.2 pF and 10 nH respectively. Both LH and RH structures are matched to 50 Ω to provide a balanced MTM structure. This MTM resonator occupies an area of about 504 mm^2, which represents a 90% miniaturization compared with a conventional closed-loop resonator [7].

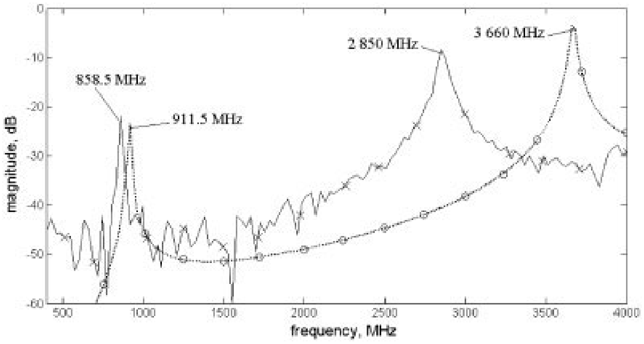

Figure 3 Simulated and experimental responses of the MTM closed-loop resonator ----o--- simulated —×— measured

The MTM closed-loop resonator was symmetrically coupled to generate a 3 dB frequency bandwidth of 9.4% at a center frequency of 900 MHz. As shown in Figure 1, the TL between points T_1 and T_2 produces a $-90°$ phase shift whereas the TL between points T_3 and T_4 provides a $-270°$ phase shift generating the constructive interference at the output port 4 and the destructive interference at the isolated port 3. From Figure 1, it is evident that the relative size of the T_3–T_4 line is rather large compared with the overall size of the filter. Therefore, to give further miniaturization, a second DF was designed by replacing the conventional $-270°$ line with a CRLH TL composed of two $+45°$ unit cells. The values of the series capacitors and the strip-line shunt inductors are 4.7 pF and 6.4 nH respectively. Figure 2 shows the miniaturized DF.

3. RESULTS

Figure 3 shows the simulated and measured S_{21} response of the weakly-coupled MTM closed-loop resonator. It is seen that the measured resonance appears at 858.5 MHz, which is a lower frequency than the simulated 911.5 MHz. This is explained as the SMD element dimensions are not taken into account by the simulator, so in the real circuit the length of the loop is slightly increased, thereby generating a lower resonant frequency compared with the simulation. The Q_u produced by the MTM closed-loop resonator is 60, similar to the simulated value of 67. By simulation it was proven that Q_u can be increased to over 100 if SMD inductors are replaced by patterned inductive lines. It is also noticeable that no harmonic resonances are generated. The second resonance that appears at 2850 MHz in the experiment and 3660 MHz in the simulation is caused by a 360° phase shift along the loop.

Figure 4 plots the S_{41} passband and S_{21} rejectband responses of

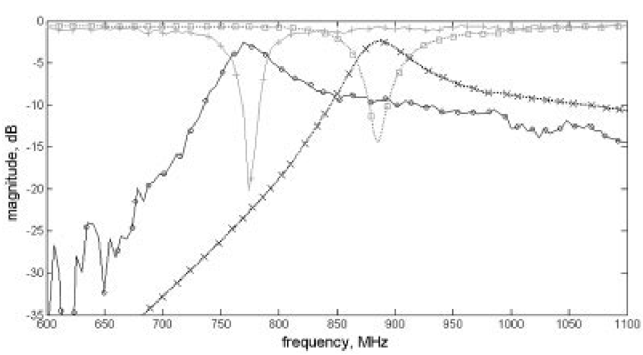

Figure 4 Simulated and experimental responses of the filter of Figure 1 —+— measured S_{21} —o— measured S_{41} ----□---- simulated S_{21} ----×---- simulated S_{41}

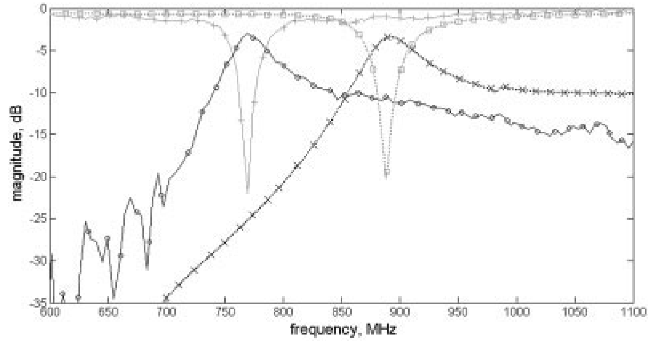

Figure 5 Simulated and experimental responses of the filter of Figure 2 —+— measured S_{21} —o— measured S_{41} ----□---- simulated S_{21} ----×---- simulated S_{41}

the DF designed with MTM closed-loop resonators. The measured operation frequency appears at 770 MHz and the simulated one at 886 MHz due to the inclusion of the SMD components. The simulated S_{41} 3 dB bandwidth is of 6.7%, and the experimental S_{41} bandwidth results of 5.9%. Maximum S_{41} transmission losses are located at around -2.5 dB for both simulations and measurements. This filter occupies an overall area of about 9900 mm^2, 64% smaller than a conventional DF [6].

The simulated and measured responses produced by the DF with the CRLH TL are plotted in Figure 5. The measured curve shows a central frequency of 770 MHz and the simulated 892 MHz. The simulated S_{41} bandwidth is of 6% and the measured bandwidth results of 4.7%. Transmission losses at port 4 are around -2.8 dB in the passband for simulation and measurement. This DF occupies an area of about 6600 mm^2, 76% smaller than a conventional one.

4. CONCLUSIONS

Two miniaturized DF's were successfully designed and implemented using zeroth-order *MTM* resonators. A size reduction of 90% was achieved for the single resonator compared with a conventional closed-loop resonator. The overall DF was miniaturized to 24% compared with conventional one. Both filters presented harmonic resonance suppression. Good agreement between simulations and measurements were achieved.

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