Complementary split ring resonators for microstrip diplexer design

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A new topology for the design of microstrip microwave diplexers, based on the use of quasi-lumped resonators, is presented. Specifically, the receiver (Rx) and transmitter (Tx) filters of the diplexer are implemented by etching complementary split ring resonators (CSRRs) in the ground plane as well as series capacitive gaps and shunt inductive strips in the upper metal level. By this means, narrowband microwave diplexers with transmission zeros can be synthesised, which allow for the improvement of Rx/Tx isolation. A prototype device operating in the 2.4–3.0 GHz frequency band is presented. Measured insertion losses are lower than 2 dB while the isolation between Rx/Tx channels is in the vicinity of 40 dB. Diplexer dimensions (29.8 × 16.3 mm), which are small on account of the semi-lumped resonators employed, and performance point to the practical application of these structures in communication transceiver front-ends.

Introduction: Complementary split rings resonators (CSRRs) have recently been reported by some of the authors [1] as key components for the synthesis of negative permittivity metamaterial microstrip lines. Combined with series capacitive gaps, CSRRs have also been used for the design of narrow bandpass structures with backward (or left-handed: LH) wave propagation in the allowed band [2]. To improve frequency selectivity and rejection beyond the allowed band, an LH CSRR/gap stage should be cascaded with the combination of a CSRR and a shunt-connected inductive strip (stub). This latter CSRR/stub stage provides a sharp fall-off at the upper transition band due to the presence of a transmission zero above, but close to, the region where signal propagation is allowed. Thus, by cascading the CSRR/gap cells with CSRR/stub combinations (the latter being of forward or right-handed (RH) nature), the synthesis of bandpass structures with selective frequency response at both band edges is possible.

In this Letter, these ideas are applied to the design of a microstrip diplexer in microstrip technology. The diplexer consists of a three-port device with a receiver (Rx) and a transmitter (Tx) filter cascaded at the output lines of a Y-junction, as shown in Fig. 1. It will be shown, by designing the Rx and Tx filters with two CSRR stages (i.e. a CSRR/gap cell cascaded with a CSRR/stub combination), it suffices to obtain good diplexer performance, namely low in-band losses for the Tx and Rx channels, and high Rx/Tx isolation. Owing to the limited number of stages and to the small size of the resonators employed, device dimensions are small compared to microwave diplexers based on fully distributed approaches [3]. Other microwave diplexers with similar dimensions, in-band losses and Rx/Tx isolation (but with lower signal rejection below the Tx band) have been recently reported by Goron et al. [4].

Diplexer design: The topology of the fabricated microstrip diplexer is shown in Fig. 2. The Tx and Rx filters have been designed to provide passbands centred at 2.4 and 3.0 GHz, respectively, with absolute bandwidths of 0.25 GHz (namely 10.3 and 8% fractional bandwidths for transmission and reception). The Rx/Tx isolation has been set to 40 dB. The equivalent circuit model of either filter is shown in Fig. 3. CSRRs are modelled by resonant tanks [5], formed by the inductance \( L_s \) and capacitance \( C_g \), which are capacitively coupled to the host line through the capacitance \( C_s \). \( C_s \) is the capacitance of the series gap, and \( L_p \) models the inductance of the grounded strips, which are connected to the lower metallic plane through vias. Finally, \( L_o \) is the line inductance. In the CSRR/stub stage two CSRRs have been used to ease the synthesis of the required filter bandwidths. The sub-index (when present) in the electrical parameters of Fig. 3 denotes the stage number.

Fig. 1 Structure of diplexer

\[ f_s = \frac{1}{2\pi \sqrt{L_s(C_s + C_g)}} \]

(1)

where \( i = 1 \) and 2 for the first and second stage, respectively. For the CSRR/stub stage, the allowed band arises at the right of the transmission zero frequency. The bandwidth of this stage can be roughly estimated from the frequency region where signal propagation is allowed (negative wave propagation). This can be inferred from the phase shift \( \phi \) of the cell, which is given by

\[ \cos(\phi) = 1 + \frac{L_s \omega^2 - 1/C_s \omega^2}{2(L_s \omega^2(1 - L_s C_s \omega^2) - 1/C_s \omega^2)} \]

(2)

due to the formulas reported in [6]. The region where \( \phi \) is real is delimited by the following frequencies:

\[ f_L = \frac{1}{2\pi \sqrt{L_s C_s}} \]

(3)

\[ f_H = \frac{1}{2\pi \sqrt{L_s C_s}} \]

(4)

Therefore, for the CSRR/gap stage, signal propagation is allowed within the interval \( f_L - f_H \).

For the CSRR/stub combination, the allowed band is located at the left of the transmission zero frequency. The phase shift is given in this case by:

\[ \cos(\phi) = 1 + \frac{L_s \omega^2}{2(L_s \omega^2(1 - L_s C_s \omega^2) - L_p/C_s)} \]

(5)

and the lower and upper limits of the allowed band are roughly given by:

\[ f_L = \frac{1}{2\pi \sqrt{L_p/C_s}} \]

(6)

\[ f_H = \frac{1}{2\pi \sqrt{L_p/C_s}} \left( 1 + \frac{4f_0^2}{L_1^2} \right) \]

(7)

Expressions (6) and (7) are valid under the approximation \( L_1 \ll L_p \), which is reasonable provided that the transmission zero frequency is separated enough from the central filter frequency (indeed the exact analytical expressions for \( f_L \) and \( f_H \) are not mathematically simple and their deduction involves tedious calculation).
Expressions (1)–(7) have been used as design guidelines to control central frequency, filter bandwidth and selectivity (transmission zeros). Care has been taken to allocate the upper (lower) transmission zero of the Tx (Rx) filter within the band for reception (transmission). This way, the targeted isolation between ports 2 and 3 can be obtained (as will be shown) to a good approximation. To determine the electrical parameters of the equivalent circuit model, adjustment by optimisation has been necessary. To this end, the commercial software Agilent Advanced Design System (ADS), which includes the electromagnetic solver Agilent Momentum, has been used. Indeed the optimiser has also been used to obtain the final geometry of the filters, where the seeding layout has been inferred from previously published expressions that link geometry to electrical parameters [5, 6]. The separation between the filters and the Y-junction has been inferred by forcing a null phase shift for the returning signal from either filter.

The diplexer has been fabricated on a Rogers RO3010 substrate (dielectric constant $\varepsilon_r = 10.2$, thickness $h = 1.27$ mm) by means of a standard photo/mask etching technique. Prior to layout definition, a metallisation was carried out for vias grounding.

Results: Fig. 4 shows the measured (by means of the Agilent 8720ET vector network analyser) transmission coefficient for the Tx and Rx filters (i.e. $S_{21}$ and $S_{31}$, respectively), as well as the measured Rx/Tx isolation ($S_{32}$). In-band losses lower than 2 dB have been measured for either filter, while return losses (also shown in Fig. 4) are better than 10 dB. The frequency response of the filters is quite symmetric and the measured isolation between ports 2 and 3 is in the vicinity of 40 dB, as desired. Remarkable also are the dimensions of the diplexer (see the region indicated in Fig. 2), which are as small as $29.8 \times 16.3$ mm (namely $0.63\lambda \times 0.34\lambda$, $\lambda$ being signal wavelength at the Tx frequency) thanks to the compact resonators employed.

Conclusions: A microstrip diplexer implemented by means of CSRRs has been presented for the first time. Device performance, as shown by the measured insertion/return losses ($IL < 2$ dB, $RL > 10$ dB) and Rx/Tx isolation ($\sim 40$ dB), is good, and dimensions are compact on account of the sub-wavelength resonators employed. For these reasons, it is thought that this type of diplexer can find application in communication transceiver front-ends.

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References