Low-Loss Directional Filters Based on Differential Band-Reject Filters With Improved Isolation Using Phase Inverter

Jakub Sorocki, Ilona Piekarz, Slawomir Gruszczynski, and Krzysztof Wincza

***Abstract*— In this letter, a novel approach to the design of directional filters (DFs) based on the differential bandstop filter and delay lines is proposed. It is shown that utilization of a phase inverter (PI) and reference line as a mode-converting phase shifter allows for obtaining theoretically ideal bandpass-to-bandstop channels isolation over an infinite bandwidth. The presented theoretical analysis is confirmed by realization of an exemplary low-loss DF with defected ground type PI covering industrial, scientific, and medical, 2.4-GHz band. The obtained measurement results show insertion loss as low as 1.1 dB and almost flat isolation response, better than 27 dB up to 6 GHz proving the validity of the presented approach.**

***Index Terms*— Differential band-reject filter (DBRF), directional filter (DF), isolation improvement, low-loss passive circuit, phase inverter (PI).**

I. Introduction

In recent years, a dynamic development of wireless systems can be observed resulting with the demand for efficient utilization of available frequency channels. In many cases, high-performance channel multiplexing devices are of need. Circuits that can be used for such applications, e.g., directional filter (DF)-based multiplexers [1], in comparison with the other multiplexing circuits, feature good impedance match over a wide frequency range. Thus, when a significant number of channels are required, the entire channels separating system can be realized by cascading separately designed filters element-by-element. In literature, various realizations of a DF can be found [2]–[6]. A new methodology of designing multistage DF was presented in [4] and [5], where the DF is constituted of two differential band-reject filters (DBRFs) with delay lines. In such an approach, the coupled-port response and through-port response of the resulting DF resemble the differential S-parameters of the constituting DBRF allowing for the synthesis of the desired DF response. However, such filters suffer from poor out-of-band isolation performance between bandpass and band-reject paths of the filter. To overcome this problem, Sun *et al.* [5] proposed to realize delay lines with corrected electrical lengths or the application of left-handed metamaterial transmission line section as one of the delay lines. However, such techniques allow improvement in isolation level only in the vicinity of the center frequency of operation.

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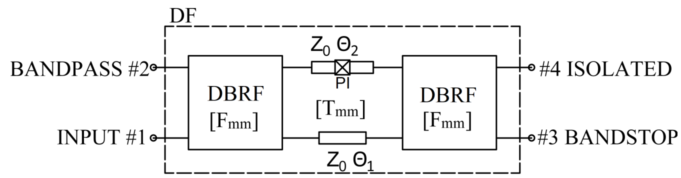


Fig. 1. Schematic of the DF realized as two DBRFs connected using proposed mode-converting circuit composed of section of transmission line and PI.

In this letter, we propose novel design approach allowing for obtaining theoretically ideal isolation with infinite bandwidth. In DBRF approach for DF realization, two of such differential filters are connected using delay lines. The delay lines can be treated as mode conversion (common-differential) differential phase shifter, and the isolation is directly related to this property, i.e., the further the phase difference from 180°, the lower the isolation level. Hence, we propose realization of a mode-converting phase shifter using phase inverter (PI) and a reference line. The theoretical analysis of the DF is provided to support the proposed approach. Moreover, the experimental verification is presented by the design and measurement of an exemplary low-loss DF with defected ground type PI covering industrial, scientific, and medical (ISM) 2.4-GHz band featuring insertion loss as low as 1.1 dB and almost flat isolation response, better than 27 dB up to 6 GHz. The obtained measurement results prove validity of the presented approach for isolation improved DFs.

II. Isolation Performance Analysis of the DBRF-Based Directional Filter

General schematic of the proposed DF realized as two DBRFs connected using two delay lines is shown in Fig. 1. Properties of the circuit can be analyzed based on its mixed-mode S-parameters derived using, e.g., signal flow graph shown in Fig. 2. Such an approach is convenient as the constitutive DBRFs are considered in terms of their 2-port mixed-mode S-parameters rather than 4-port single-ended ones. As it

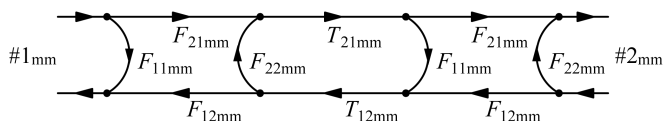


Fig. 2. Mixed-mode signal flow graph of the directional filter shown in Fig. 1 (mixed-mode ports, $\#1_{mm}$ and $\#2_{mm}$, are between single-ended ports—#1, #2 and #3, #4) allowing to analyze the DF response based on the mixed-mode S-parameters of the constitutive DBRFs (F_{xxmm}) and delay line (T_{xxmm}), respectively. Moreover, a reciprocity is assumed; hence, $F_{11\,mm} = F_{22\,mm}$ and $F_{21\,mm} = F_{12\,mm}$ and it is assumed that delay lines are lossless, ideally matched, and isolated.

was shown in [5], the bandpass S_{21} and bandstop S_{31} response of the DF resembles differential transmission F_{21dd} and reflection F_{11dd}, respectively, of the constitutive DBRF. The isolation response between bandpass and bandstop outputs on the other hand can be expressed as

$$\begin{aligned} S_{32} &= 0.5(S_{21cc} - S_{21dd}) \\ &= 0.5\left(\frac{F_{21cc}^2 T_{21dd}}{1 - F_{11cc}^2 T_{11dd}^2} - \frac{F_{21dd}^2 T_{21dd}}{1 - F_{11dd}^2 T_{11dd}^2}\right). \end{aligned} \quad (1)$$

The magnitude of isolation is zero when the expression (1) is equal to zero leading to the condition

$$|T_{21dd}|\left|\frac{F_{21cc}^2}{1 - F_{11cc}^2 T_{11dd}^2} - \frac{F_{21dd}^2}{1 - F_{11dd}^2 T_{11dd}^2}\right| = 0. \quad (2)$$

Since the parameters of DBRF are not subject to change, an ideal isolation is obtained when $|T_{21dd}| = |T_1 + T_2| = 0$, where T_1 and T_2 are the single-ended transmission coefficients through delay lines. The condition (2) holds for circuits shown, e.g., in [5] only in the vicinity of the center frequency, since 180° phase difference between T_1 and T_2 is obtained only at the center frequency. On the other hand, the condition (2) could be satisfied over infinite bandwidth in the case when $T_1 = -T_2$. Therefore, we propose realization of one delay line as a PI for which $T_2 = -e^{-j\theta 2}$, while the other is a transmission line section for which $T_1 = e^{-j\theta 1}$ and maintaining $\theta_1 = \theta_2 = \theta$. The required electrical length θ can be found similarly as in [5] to ensure ideal return loss of port #1 at the center frequency of operation.

The design of the proposed DF is done in the following two-step manner.

1) First, a DBRF is designed such that the differential transmission and reflection coefficients meet the requirements for the DF bandpass and bandstop response.
2) Next, two of such DBRF are connected using the proposed delay circuit for which the required electrical length is determined from electromagnetically (EM) calculated filter response. It is important to select the physical realization of the PI in such a way to suit the overall design in terms of technological compatibility and required frequency response.

III. Experimental Results

To experimentally verify the proposed approach, an exemplary low-loss DF was designed, manufactured, and measured with the focus being on the isolation response. A first-order DF ($Z_0 = 50\ \Omega$) covering the ISM 2.4-GHz band was

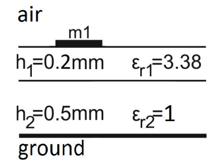


Fig. 3. Cross-sectional view of an utilized dielectric stack-up. Top thin laminate with metal layer m_1 is suspended in air over the ground plane.

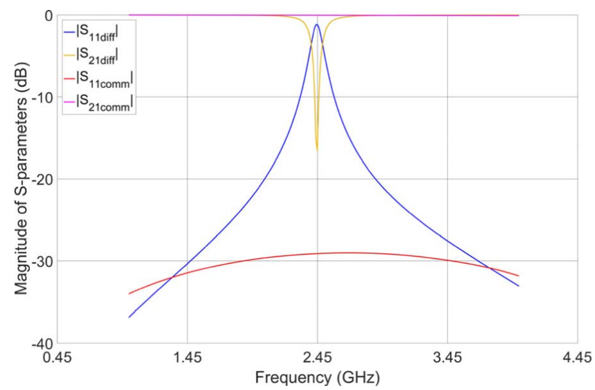


Fig. 4. EM calculated common-differential frequency response of the designed DBRF.

realized in the dielectric structure shown in Fig. 3. Suspended microstrip technique was used to reduce the total loss within the structure. First, the required DBRF was realized as a single-ended notch filter composed of one quarter-wavelength (at $f_0 = 2.45$ GHz) coupled-line section having coupled and isolated ports terminated in short and open which was then converted into differential filter. To ensure the filter's required 100-MHz bandwidth is met, coupling to the main transmission line was set to $k = 0.245$ ($C = 12.22$ dB). In addition, to ensure an appropriate common mode all-pass response as well as to improve the out-of-band attenuation of differential mode reflection response of the DBRF, the coupled-line section was compensated, similarly as in [7] using quasi-lumped approach to equalize uneven coupling coefficients. EM calculated common-differential frequency response of the filter is shown in Fig. 4.

Having designed the DBRF filter, electrical length of the delay section was found to provide ideal impedance match at the center frequency and equals $\theta = 68°$. The PI was realized as a ground defected structure with via connection between signal and ground strips providing phase inversion. Such configuration was selected due to ease of implementation and manufacturing as well as relatively wideband operation; however, the proposed design approach is not restricted to this realization. Moreover, the DF utilizing the enhanced approach presented in [5] where mode-converting circuit is realized using right- and left-handed transmission line sections of appropriate electrical lengths was designed for reference purposes. A comparison of the EM calculated frequency response of both circuits is shown in Fig. 5. As it can be seen, the proposed approach allows for significant improvement of isolation performance in term of achieving high-isolation level over wide bandwidth, while general bandpass and bandstop paths' response is maintained.

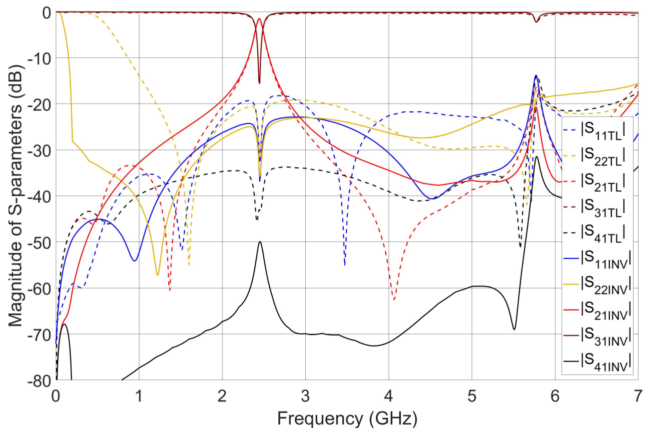
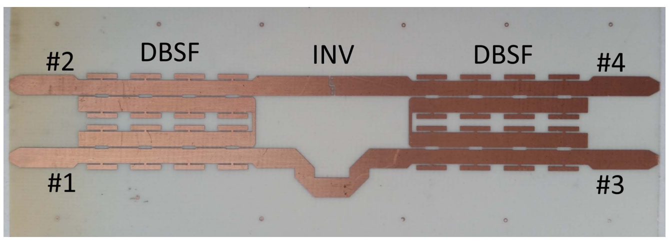
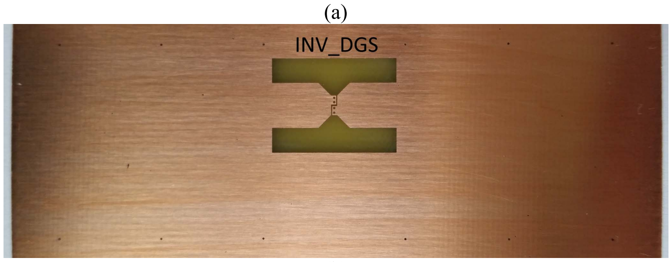


Fig. 5. Comparison of DFs' performance where identical DBRFs are used, whereas mode-converting circuit is realized as right- and left-handed transmission lines (dashed line) similarly as in the enhanced solution shown in [5] and with the proposed approach utilizing PI (solid line) having layout as seen in Fig. 6. Result of EM calculations.



(a)



(b)

Fig. 6. Pictures of (a) top suspended laminate with metal m_1 and (b) ground plane of the manufactured low-loss DF. Two identical DBRFs as well as delay section with defected ground structure PI are visible.

The designed circuit was manufactured and measured. The patterned ground plane was realized on top of the FR4 laminate due to the ease of manufacturing and additional mechanical strength of the entire circuit while having no effect on the electrical performance. Photographs of the circuit are shown in Fig. 6, where DBRF filter as well as delay section with realized PI can be clearly visible. The measurement results are shown in Fig. 7 for a broad frequency range. As seen, the circuit features high, almost flat isolation response up to 6 GHz with lowest value of 27 dB at the center frequency. Above that frequency, the response is deteriorated mostly due to frequency response of the DBRF. The center frequency is shifted to $f_0 = 2.76$ GHz due to finite manufacturing tolerances. Measured insertion loss at f_0 is equal IL $= 1.11$ dB, while return loss at the input port equals $\mathrm{RL}_{11} = 27$ dB. In addition, the strong influence of the utilized PI on return losses at bandpass port #2 is visible. However, since port #2 provides only relatively narrow bandpass response, the out-of-band impedance match is of lesser importance. In general, the return losses of port pairs—#1, #3 and #2, #4—are inherently different due to nonsymmetrical nature of the mode-converting circuit and resulting appearance of cross modes.

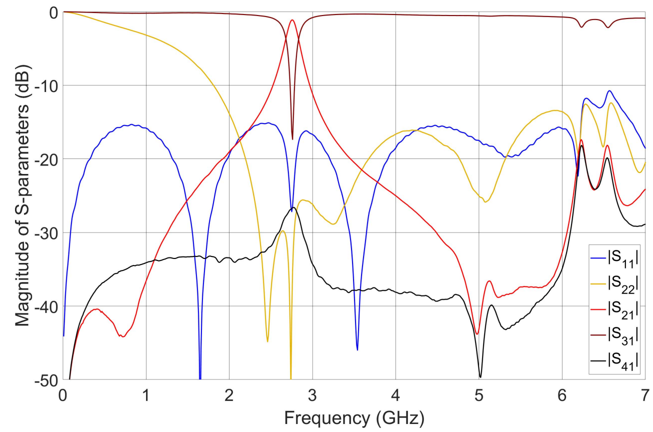


Fig. 7. Measured frequency characteristics of the manufactured low-loss DF shown in Fig. 6. The obtained high level of isolation (black solid line) over wide bandwidth can be clearly visible.

IV. Conclusion

A novel approach to the design of DFs based on DBRFs and delay lines was proposed. It was shown that introduction of PI instead of one delay line realizing mode-inverting circuit allows in theory for bandpass-to-bandstop paths isolation being ideal over an infinite bandwidth. Such a property is of need for modern frequency multiplexer applications to reduce crosstalk. An exemplary low-loss DF was designed, manufactured, and measured to experimentally verify the proposed approach. The measured circuit features almost flat isolation response, better than 27 dB up to 6 GHz proving its applicability.

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