Frequency Multiplexer with Improved Selectivity Using Asymmetric Response Directional Filters

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

***Abstract*— In this paper, a novel approach to the design of frequency multiplexers consisting of cascaded directional filters is proposed. It is shown that when channels are spaced closely enough, their selectivity can be improved without increasing filters' order by taking advantage of two phenomena. Asymmetric frequency response of a constitutive directional filter allows to increase the attenuation slope on one side of the multiplexer channel. Additionally, the slope on the other side can be increased due to the creation of additional transmission zero resulting from the fact that bandstop response of previous directional filters within the cascade affects directly the response of the following channel. Theoretical analysis is provided together with the applicability condition and multiplexer design procedure. Moreover, an exemplary four-channel S-band multiplexer was manufactured and measured showing the selectivity improvement of as much as ~1.3 times.**

Keywords—directional filter; frequency multiplexer.

I. Introduction

Modern communication systems require an integration of many frequency bands with preferably a single antenna covering the desired frequencies (e.g. GPS, GSM, WLAN and UWB bands as in [1]). For such front-end systems, there is a need for broadband antennas on one hand, and devices for multiplexing and de-multiplexing signals in the frequency domain on the other hand. Devices constructed of directional filters (DFs) can perform multiplexing function [2], while featuring the advantage of low reflection at the input over wide bandwidth and modular topology, in which filters for each band can be designed separately. Furthermore, such devices can easily be integrated with planar UWB antennas and active circuits, effectively increasing system's integrity and lowering its cost. Channel selectivity of such multiplexers is dependent from the realization and order of constitutive DFs. In literature, different realizations have been proposed [3]-[8]. In [3] a higher order filter is presented where more than one loop resonator is used. However, the design complexity increases with the order, since different couplings between resonators need to be realized. Another approach is to introduce transmission zeroes (TZ) in the passband response of constitutive DFs, as shown e.g. in [4]-[7] where two identical filters are appropriately cascaded. However, location of symmetric TZs, hence the selectivity increase is dependent and limited by the filter realization.

In this paper, we propose a novel approach to the design of frequency multiplexers based on directional filters which allows for channels` selectivity improvement. When channels are spaced closely enough, one can take advantage of two different phenomena at once. Realization of an asymmetric response directional filter allows to increase the attenuation slope on one side of the multiplexer channel while the slope on the other side can be increased by creation of an additional transmission zero resulting from the fact that the bandstop response of previous directional filters within the cascade affects directly the response of the following channel. As a result, the channel response features symmetric TZs located closer to its center frequency than in case when constitutive DFs feature symmetric TZ. Theoretical analysis is provided along with the applicability condition and multiplexer design procedure. Moreover, an exemplary four-channel S-band multiplexer was manufactured and measured proving the usability of the proposed technique.

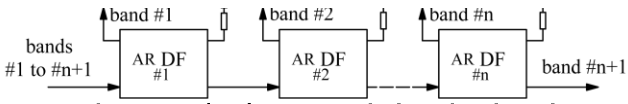

Fig. 1. General concept of a frequency multiplexer based on directional filters. Selectivity of closely enough spaced channels can be improved by realization of asymmetric response DFs and by taking advantage coming from the influence of the prevous channels on the response of the following channels.

II. Theoretical Analysis

In general, the proposed frequency multiplexer consists of an N number of cascaded DFs allowing to separate n frequency bands from the input spectrum, as seen in Fig. 1. The response of n^{th} channel depends on the bandpass characteristic of #n^{th} DF. However, since DFs are cascaded is such a way that bandstop output of the previous filter is fed to the input of the subsequent one, the bandstop responses of all previous filters affect the n^{th} channel response as well. When frequency channels are distantly spaced, such a property does not influence the channels` in-band performance. However, when spacing between channels is close enough, such a property can be utilized to improve the frequency selectivity for each band while maintaining DFs` size and insertion losses (excluding channel #1). In such a case, the frequency multiplexer can be composed of DFs having asymmetric frequency response resulting from one TZ being closer to center frequency compared to the case of evenly spaced TZs. The asymmetry of TZs with respect to the DF's center frequency allows to obtain

This work was supported by the National Science Centre, Poland under contract no. 2014/13/N/ST7/01961 and no. 2016/20/T/ST7/00202.

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a sharper attenuation slope on one side of the passband at the expense of a lower slope sharpness on the other side. However, an additional TZ appears at the center frequency of the previous channel due to its bandstop response allowing to compensate and increase the deteriorated attenuation slope. In such a case, the resulting multiplexer channel can feature symmetrically placed transmission zeroes closer to its center frequency. The condition for maximal channel spacing required in the proposed approach is as follows:

$$|f_{0n} - f_{0(n-1)}| \leq |f_{0n} - f_{TZsymn}| \qquad (1)$$

where f_{0n} and $f_{0(n\text{-}1)}$ are center frequencies of adjacent channels while f_{TZsymn} is a location of TZs for symmetrical response DF. Condition (1) can also be used to determine an appropriate location of TZ in the asymmetric response DF assuming that the second TZ will appear at $f_{0(n\text{-}1)}$.

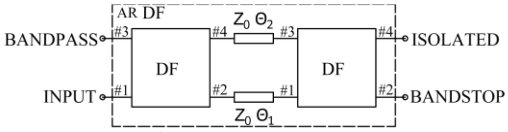

Fig. 2. Schematic diagram of the utilized ARDF. Appropriate connection of two DFs with no TZs allows to introduce TZs into bandpass path [6]. Location of TZs is controlled by the sum of electrical lengths of the connecting lines.

The building block of the proposed frequency multiplexer is an asymmetric response directional filter (ARDF) with a preference for topology allowing for flexible design of TZs location. A well suitable realization is the one introduced in [6] which is adopted for this study. A schematic diagram of the ARDF is shown in Fig. 2 where two identical symmetric frequency response DFs with no TZs are connected using transmission lines having electrical lengths equal to θ_1 and θ_2. The response of bandpass S_{BPn} and bandstop S_{BSn} paths can be determined using signal flow graph analysis to be:

$$S_{BPn} = S_{21n} = S_{12n} = \frac{S_{Sn}^2 S_{Pn}\, T_{1n} T_{2n} + S_{Pn}\left(1 - S_{Pn}^2 T_{1n} T_{2n}\right)}{1 - S_{Pn}^2 T_{1n} T_{2n}} \qquad (2)$$

$$S_{BSn} = S_{31n} = S_{13n} = \frac{S_{Sn}^2 T_{1n}}{1 - S_{Pn}^2 T_{1n} T_{2n}} \qquad (3)$$

where $T_{1n,\ 2n} = e^{-j\theta 1,\ \theta 2}$. The location of transmission zeroes is controlled by the selection of the sum $\theta_1 + \theta_2$. Having fixed parameters of the basic DF, one can calculate direct relation between the sum $\theta_1 + \theta_2$ and the location of transmission zeroes f_{TZ} from (2):

$$e^{-j(\theta_{01} + \theta_{02})\frac{f_{TZ}}{f_0}} = \frac{1}{S_{Sn}^2 - S_{Pn}^2}\Big|_{@f_{TZ}} \Rightarrow \theta_{01} + \theta_{02} = \left(\varphi_{Pn}|_{@f_{TZ}}\right)\frac{-2f_0}{f_{TZ}} \qquad (4)$$

where S_{Sn} and S_{Pn} are the appropriate S-parameters of the basic filter, φ_{Pn} and φ_{Sn} are phases of S_{Pn} and S_{Sn}, f_0 is the center frequency of the filter at which the electrical lengths θ_{01}, θ_{02} are defined and f_{TZ} is the designed location of a transmission zero. Equation (4) holds under the assumption $(\varphi_{Pn} - \varphi_{Sn}) = \pm 0.5k\pi$; $k = 0,1,2\ldots$ which is always true for the ideal circuit.

III. Frequency Multiplexer Design

In general, a multiplexer constructed of DFs allows one to separately design filters for each channel and additionally to freely modify their number. In case of the proposed design, when the number of channels and their bandwidths are established in the first step, one need to design basic DFs providing appropriate bandwidth and ripples level in the bandpass/bandstop paths. Next, a modified DF is designed for each channel with appropriately placed transmission zeros (see condition (1)) to optimize and improve channels` selectivity and stopband attenuation. Finally, the multiplexer is assembled out of the designed blocks.

To verify and evaluate the proposed approach, an exemplary four-channel S-band multiplexer was designed, manufactured and measured. Each channel is being separated by ARDF shown in Section II composed of two single loop traveling wave DFs. First channel was assumed to be located at the center frequency f_{01} = 2.3 GHz with 100 MHz bandwidth (quality factor $Q \approx 22$). As it has been explained in Section II, response of the first channel cannot be improved, hence optimal design of DF #1` frequency response is with symmetrically placed transmission zeros. The utilized ARDF when $\theta_1 = \theta_2 = 0°$ can provide zeroes distanced from f_{01} by ±0.23 GHz. Hence, to investigate the selectivity increase with respect to the distance from the previous channel, spacing's between 2nd - 4th channels, which are further in the cascade, were selected to be 0.14 GHz, 0.18 GHz and 0.22 GHz, respectively. Location of the upper transmission zero in DF #2 - #4 was selected in such a way to provide symmetrical response of channels #2 - #4 when combined with the one resulting from the previous channel. Moreover, each channel is assumed to have quality factor Q identical to the one of channel #1. As a drawback, the higher frequency of the channel, the further distance of symmetrically placed TZ from the center frequency. A summary of parameters of each multiplexing channel resulting from parameters of ARDFs is provided in Table I.

TABLE I
Theoretical and Measured Parameters of the Designed Multiplexer in Respect to Parameters of Constituting ARDFs

	data source	**$\theta_1 + \theta_2$ (deg)**	**$f_{0n} \pm f_{TZn}$ (GHz)**	**f_{0n} (GHz)**	**BW_{3dB} (GHz)**	**SEL**
ARDF #1	circuit	sym TZ	-0.23, 0.23	2.30	0.105	0.345
	model	-	-	-	-	-
MUX ch. **#1**	EM calc	-	-0.24, 0.23	2.30	0.097	0.345
	meas	-	-0.21, 0.22	2.24	0.091	0.299
ARDF #2	circuit	sym TZ	-0.25, 0.25	2.44	0.111	0.297
	model	20.4	-0.39, 0.14	2.44	0.11	0.330
MUX ch. **#2**	EM calc	-	-0.14, 0.13	2.44	0.101	0.471
	meas	-	-0.13, 0.16	2.37	0.090	0.383
ARDF #3	circuit	sym TZ	-0.27, 0.27	2.62	0.119	0.344
	model	23.2	-0.44, 0.18	2.62	0.139	0.384
MUX ch. **#3**	EM calc	-	-0.17, 0.15	2.61	0.112	0.450
	meas	-	-0.16, 0.18	2.54	0.098	0.310
ASDF #4	circuit	sym TZ	-0.29, 0.29	2.84	0.129	0.343
	model	9.2	-0.36, 0.22	2.84	0.129	0.342
MUX ch. **#4**	EM calc	-	-0.22, 0.22	2.83	0.124	0.383
	meas	-	-0.21, 0.25	2.75	0.113	0.330

ARDF – constitutive directional filter parameters, MUX – resulting multiplexers` channel parameters; data source: circuit model, EM calc*ulated*, meas*ured*; $\theta_1 + \theta_2$ calculated using (4); sym TZ – symmetrical transmission zeroes; SEL – selectivity defined as a ratio of bandwidths BW_{3dB}/BW_{23dB}.

The utilized DF is constituted of wave-long loop resonators with input/output coupling realized using coupled-line directional couplers. For the assumed Q, the required coupling level for each coupler equals $k \approx 0.31$ (C = 10.17 dB,

Z_0 = 50 Ω). A single-layer microstrip structure on Arlon 25N laminate (permittivity ε_r = 3.38, loss tangent $tan\delta$ = 0.0025, thickness h = 0.762 mm) was used for the design due to the ease of manufacturing and realization of aforementioned edge-coupled directional couplers. Layout of the directional filter was designed in such a way to ensure the adjacent resonant loops remain uncoupled and in case of ch. #1 to allow for realization of symmetrically placed transmission zeroes (see Fig. 3). Next, two instances of the designed basic loop resonators are connected with transmission lines having appropriate electrical lengths to create asymmetrically placed transmission zeroes in the desired locations (see Table I). Moreover, when the circuit size is also of interest, one can use the miniaturization technique as shown e.g. in [8]. ARDF for each channel was designed in an identical manner. Finally, four ARDFs have been cascaded to realize the frequency multiplexer and verified using EM simulations (see Table I).

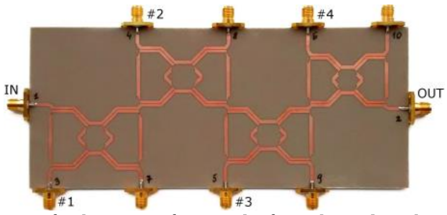

Fig. 3. Picture of the manufacteured four-channel S-band frequency multiplexer realized as cascade connection of four ARDFs. Each ARDF realized as two single-loop DFs connected using transmission line sections can be clearly visible. Area occupied by each channels` filter equals 45.47 x 30.48 mm, 45.25 x 29.03 mm, 42.25 x 27.40 mm and 39.02 x 25.63 mm, respectively.

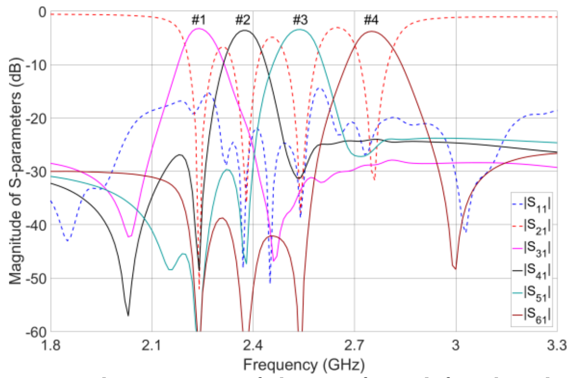

Fig. 4. Measured S-parameters of the manufactured four-channel S-band frequency multiplexer. Response of the ch. #1 is identical to the one of the utilized DF #1 while in response of ch. #2 - #4 additional transmission zeroes are visible alowing for channels` selectivity increase.

IV. Experimental Results

The designed multiplexer has been manufactured and measured. A picture of the realized circuit is show in Fig. 3 whereas the measured S-parameters are presented in 4. As predicted, additional transmission zeroes allowing to increase the overall selectivity of the channels, closer to the center frequency in channels #2 - #4 are clearly visible. The measured parameters are summarized in Table I. Center frequencies and location of TZs for each channel are slightly shifted downwards due to the limited manufacturing accuracy, however, it needs to be underlined that the general relationships between all parameters within the multiplexer are maintained. Moreover, the measured return losses at the input port as well as isolations from the input to ports #7, #8, #9 and #10 are better than 15 dB over the entire bandwidth. Insertion loss for each channel equal 3.26 dB, 3.63 dB, 3.45 dB and 3.80 dB, respectively while total (radiated, dielectric and conductor) losses are below 2.4 dB over the operational bandwidth. Selectivity of ch. #2 using the proposed approach can be increased theoretically ~1.6 (meas. 1.3) times, ch. #3 ~1.3 (meas. 1) times, while ch. #4 ~1.1 (meas. 1) times with respect to the case when ideal DFs feature symmetrically placed transmission zeroes and no interaction between channels is assumed. Moreover, comparing to the four-channel multiplexer shown in [10] composed of four second-order bandpass filters combined by two T-shaped resonators, selectivity for the ~2.4 GHz channel in the proposed approach is ~1.41 times higher at the expense of higher insertion loss, however, keeping in-band return losses lower. The proposed multiplexer allows for selection of frequency channels being spaced closely without the need of increasing the filters' order.

V. Conclusion

Multiplexers with improved selectivity using asymmetric response DFs were proposed. The increase of selectivity is achieved by realization of an appropriate asymmetric response of constitutive DFs in combination with a cascaded filters design approach. The sharper slope on one side of the n^{th} channel is ensured by the n^{th} DF`s response while on the other side by the stopband response of the $(n\text{-}1)^{th}$ one. The constructed exemplary four-channel S-band multiplexer featuring as high as ~1.6 (meas. ~1.3) times increase of selectivity allowed to prove usability of the proposed method.

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