Cascaded Loops Directional Filter with Transmission Zeroes for Multiplexing Applications

Jakub Sorocki, Ilona Piekarz, Slawomir Gruszczynski, and Krzysztof Wincza
AGH University of Science and Technology
Mickiewicza 30 Av., 30-059 Krakow, Poland
jakub.sorocki@agh.edu.pl

Abstract—**In this paper, a new design of a traveling wave loop directional filter allowing for realization of transmission zeroes has been proposed. In order to introduce transmission zeroes to bandpass branch of the filter, two loops have been cascaded using transmission line sections. Theoretical analysis of the circuit has been provided giving the insight into behavior of the appearing transmission zeroes related to electrical lengths of the loops' connecting segment. Performance of the presented approach has been verified by the design and measurements of an exemplary cascaded single-loops directional filter with two symmetrically placed transmission zeroes covering ISM 2.4 GHz band. The obtained results prove the usefulness of the presented approach.**

Keywords—directional filter; traveling wave; loop resonator; transmission zero; band separation multiplexer; coupled-line directional coupler.

I. Introduction

In modern telecommunication systems multi-band operation with the use of a single aperture and analog band multiplexing as well as integration with other subsystems is very important, since such an approach allows for miniaturization of the entire system and cost minimization in case of high-volume production. In such systems UWB antennas are well suitable and are commonly used [1]-[3]. In literature, many different UWB antennas can be found, however the most popular ones are printed monopoles, since they are simple in fabrication, and therefore, they feature low-cost as well as wide bandwidth and omnidirectional radiation pattern. Integration of many different subsystems (i.e. GPS, GSM, WLAN) and utilization of signal multiplexers allows for appropriate band separation and obtaining high level of integration, while maintain independence of each subsystem. For the purpose of analog multiplexing signals of different frequencies, directional filters are very useful [4]-[16], since they allow for band separation and provide proper filtering of the band of interest. Basic concept of such a system is presented in Fig. 1. The advantage of directional filters' application is that the filter for each band is designed separately and the resulting multiplexer design is very flexible and can be modified without redesigning of the entire structure. Moreover, such filters feature low cost and require simpler structure, compatible with the one needed for planar UWB antenna realization.

Different approaches of directional filters' realization have been presented in literature, e.g. methods utilizing traveling wave loop resonators [4]-[7], half-wavelength resonators [11], differential band rejection filters [12]-[14]; to provide bandpass and bandstop operation. Realization of such filters very often requires high selectivity on the bandpass output. One of the methods is to increase the order of a filter, however such an approach increases the design complexity since couplers with different coupling level for adjacent loops in case of loop filters need to be provided or different stages of higher order band rejection filters need to be designed. Alternatively, it has been shown in e.g. [11]-[15] that by cascading two identical directional filters and connecting them with appropriate transmission line sections, one can introduce transmission zeroes what allows to increase selectivity of the filter while maintaining similar design complexity.

In this paper, we present a new design of cascaded loop directional filters. In contrary to the circuits presented in literature, the proposed circuit allows for reduction of connecting transmission lines, hence minimization of insertion losses, while providing an improved selectivity at the bandpass output by additional transmission zeroes. Theoretical analysis of the circuit has been provided giving the insight into the behavior of appearance of transmission zeroes related to the electrical lengths of loops connecting transmission lines. An exemplary cascaded directional filter covering ISM 2.4 GHz has been developed and manufactured proving applicability of the proposed approach.

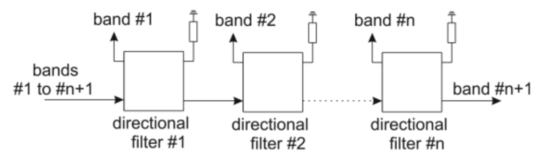

Fig. 1. General concept of a band separation multiplexer using directional filters.

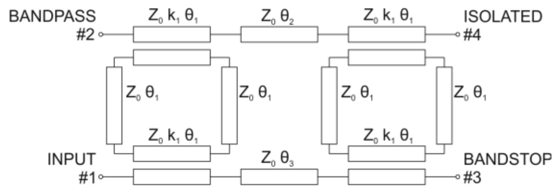

Fig. 2. Schematic diagram of two cascaded single-loop coupled-line directional filters connected using transmission line sections. Band of interest is coupled from port #1 to port #2 while the rest of the input spectrum is transmitted to port #3. Electrical length of θ_1 equal 90° at centre frequency f_0.

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II. Directional Filter With Transmission Zeroes

General schematic of the proposed directional filter realization is presented in Fig. 2. A single traveling wave loop directional filter is composed of two quarter-wave-long transmission line sections and two quadrature coupled-line directional couplers what creates a wave-long loop providing resonance at a center frequency and allows for coupling the band of interest from input port #1 to bandpass port #2 while creating bandstop at port #3. The bandwidth of such a filter depends on the coupling level k_1 of the couplers. For relatively weak coupling, the relation between coupling level and loaded quality factor, hence bandwidth of the filter, can be described by the approximate equation [4]:

$$k_1^2 \approx \frac{\pi}{Q_L} \tag{1}$$

where $Q_L = f_0/(f_u\text{-}f_l)$, f_0 is the center frequency of the filter and f_u, f_l are lower and upper 3-dB cut-off frequencies. In the proposed approach, two of such loop directional filters have been cascaded using transmission lines. It is then worth investigating the impact of electrical lengths θ_2 and θ_3 of the connecting lines on the filter's characteristics, especially bandpass selectivity.

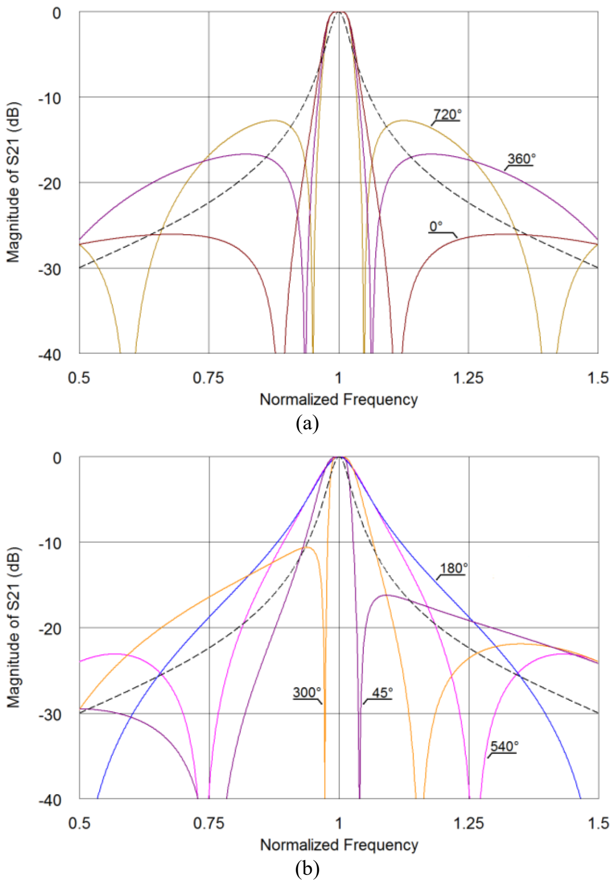


Fig. 3. Calculated magnitude of S_{21} for bandpass output of the proposed directional filter shown in Fig. 2 for a given coupling of directional couplers (here k_1 = 0.34) and different sums of electrical lengths θ_2 and θ_3 of connecting transmission lines. Transmission zeroes placed symmetricaly (a), transmision zeros placed asymmetricaly and far from center frequency (b).

It has been found that only sum of $\theta_2 + \theta_3$ need to be considered regarding the introduction of transmission zeros. An investigation has been conducted on influence of different sums of electrical lengths θ_2 and θ_3 of connecting transmission lines and a given coupling of directional couplers on bandpass characteristics and the results are shown in Fig. 3. It can be seen that for sum being multiples of π, i.e. $\theta_2 + \theta_3 = n{\cdot}\pi$ (n = 0, 1, 2,…), one can obtain transmission zeroes placed symmetrically around the center frequency. However, the longer the line the higher attenuation rate but the lower bandstop attenuation. On the other hand, while sum is a multiple of $\pi/2$ $\theta_2 + \theta_3 = n{\cdot}\pi + \pi/2$ (n = 0, 1, 2,…), the transmission zeroes are located far from the center frequency and selectivity of the filter is much worse than in case of a single loop. For a sum being in the range of $\theta_2 + \theta_3 \in (0; \pi/2)$ one can obtain asymmetric filter response and upper transmission zeroes can be brought closer to the center frequency. While for a sum being in the range of $\theta_2 + \theta_3 \in (\pi/2; \pi)$ one can obtain asymmetric filter response and lower transmission zeroes can be brought closer to the center frequency. Moreover, the location of transmission zeroes changes accordingly with changing coupling of directional couplers and quality factor of the filter, however, the character of transmission zeroes location is only related to the sum of electrical lengths of connecting lines.

III. Experimental Results

The presented in Section II analysis of the transmission zeroes realization has been experimentally verified by the design and measurements of an exemplary cascaded single-loop directional filter. For proof-of-concept realization, an ISM 2.4 GHz band has been selected and the center frequency f_0 = 2.45 GHz for bandpass output with 100 MHz bandwidth (4%) have been assumed in system impedance Z_0 = 50 Ω. Moreover, sum of electrical lengths θ_2 and θ_3 has been selected to be 0° in order to provide two symmetrically placed transmission zeroes at bandpass port #2 with, according to presented theoretical analysis, highest level of attenuation in band-stop region. For the filter design a dielectric structure shown in Fig. 4 has been selected, since it allows for realization of relatively wide range of directional coupler`s coupling coefficients.

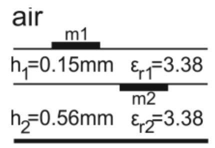
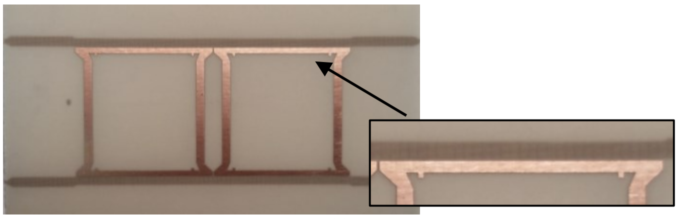
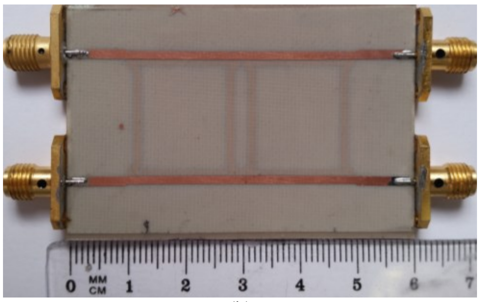


Fig. 4. Cross sectional view of the dielectric structure selected for the design. Arlon 25N, 6 mil thick laminat has been bonded with 20 mil thick Arlon 25N laminate using prepreg.

The proposed directional filter is composed of two cascaded identical single-loop segments. A single-loop filter is composed of two identical, quarter-wave long coupled-line directional couplers providing power coupling to and from traveling wave loop resonator and two quarter-wave long transmission line section to realize together with couplers, a wave-long loop. Loaded quality factor of the filter, hence bandwidth is related to coupling level of the directional couplers and its coarse value can be found based on (1). For the assumed design parameters quality factor equals $Q_L = 24.5$ hence $k_1 = 0.358$ ($C = 8.92$ dB, $Z_{oe} = 72.7\ \Omega$, $Z_{oo} = 34.4\ \Omega$).



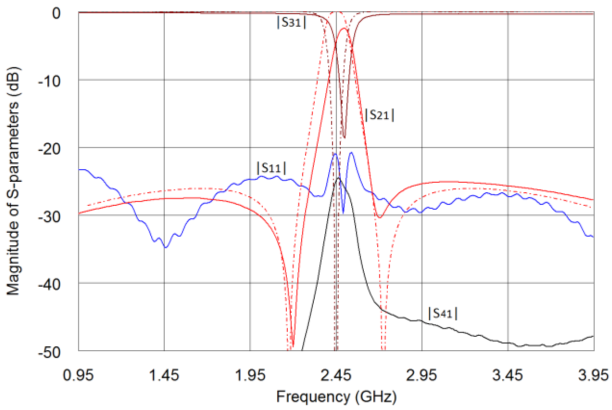
(a)



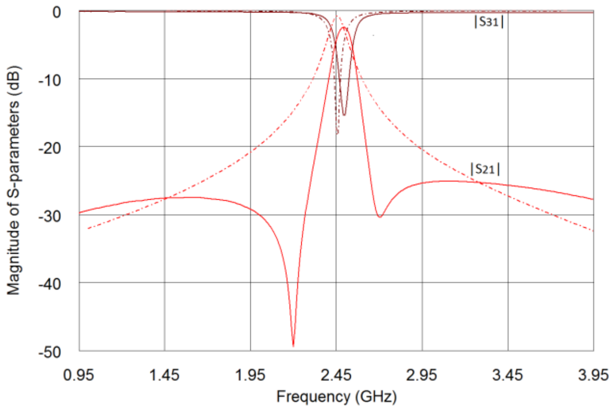
(b)

Fig. 5. Middle (m_2 side) with close-up on directional coupler (a) and top (m_1 side) (b) view of the manufactured cascaded directional filter. The overal size of the circuit equals 40.9 x 23.1 mm (not including input transmission lines).

Moreover, in this particular realization two single-loop filters are connected with 0° transmission line sections and directional couplers need to be designed is such a way that adjacent transmission lines inside cascaded loops connected to these couplers remain uncoupled to each other. For that purpose, a broadside coupled-line coupler has been realized on metal m_1 and m_2 and two output lines have been appropriately folded (see close-up on Fig. 8a) and resulting discontinuity compensated. Having designed the single loop filter, two such circuits have been cascaded and the entire circuit has been electromagnetically (EM) calculated. The designed exemplary cascaded directional filter as well as the single-loop filter have been manufactured and measured. A picture of the cascaded circuit is shown in Fig. 5, whereas a comparison between measured and ideal circuit calculations of S-parameters of the cascaded directional filter is presented in Fig. 6a. Moreover, a comparison of bandpass output characteristic of the manufactured cascaded and single-loop directional filters has been presented in Fig. 6b. As it can be seen, the exemplary manufactured circuit features good electrical performance in terms of bandpass characteristics. As predicted, much better selectivity has been obtained in the proposed circuit in comparison to the single-loop one. Two transmission zeroes (TZ) and attenuation level are in close agreement to the predicted one. Center frequency has slightly shifted to $f_0 = 2.49$ GHz while measured width of the passband equals 104 MHz. Quality factor $Q_{Lm} = 23.94$ which is close to the assumed one. Transmission zeroes are almost symmetrically located around the center frequency at 2.2 GHz and 2.7 GHz. Slight shift is a result of non-zero physical connection between cascaded loops. Isolation between bandpass and bandstop outputs equals $I = 25$ dB, return losses are equal $RL = 30$ dB while measured insertion losses are equal $IL = 2.41$ dB, all measured at the center frequency. The discrepancy between measured and ideal circuit calculated S-parameters is caused by losses as well as different than the assumed one thickness of bonding prepreg (upper and lower laminates have been bonded in heat treated process). Variation in thickness resulted in slight change in electrical lengths of transmission lines and slight change of coupling coefficient of the coupler what translated to shift of the center frequency and wider 3-dB band of operation.



(a)



(b)

Fig. 6. Measured S-parameters of the manufactured cascaded single-loop directional filter ($\theta_2 + \theta_3 = 0°$) (solid lines) in comparision with ideal elements circuit (a) and in comparision to EM calculated S-parameters of the single-loop directional filter.

IV. Conclusion

The concept of a traveling wave directional filter allowing for realization of transmission zeroes has been proposed. Introduction of transmission zeroes to bandpass branch has been achieved by means of cascading of two identical single-loop filters using transmission line sections. Impact of different electrical lengths of connecting lines on the bandpass characteristics has been investigated and described. The developed exemplary directional filter operates within ISM 2.4 GHz band and features two almost symmetrically placed transmission zeroes. Moreover, the proposed design is easily scalable for different frequency bands and is not frequency limited which makes it well suitable for band multiplexing applications.

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