Miniaturized Directional Filter Multiplexer for Band Separation in UWB Antenna Systems

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

***Abstract*—In this paper, new design of miniaturized coupled-line directional filter multiplexer allowing for band separation in UWB antenna systems has been proposed. To achieve small size of the directional filters, hence entire multiplexer, directional couplers constituting the filter have been miniaturized following the approach, in which the coupler is realized as a connection of tightly coupled and uncoupled lines. Moreover, sections of quarter-wave-long transmission lines have been designed with quasi-lumped elements approach, which allows for further miniaturization of the structure. Theoretical analysis of the circuit has been provided. Moreover, performance of the presented approach has been verified by the design and measurement of an exemplary single directional filter multiplexer covering ISM 2.4 GHz band.**

Keywords—UWB antenna; band separation multiplexer; directional filter; miniaturized directional coupler.

I. INTRODUCTION

Modern communication systems require a single antenna to cover several allocated wireless frequency bands. Such an approach allows for integration of different subsystems to share the same antenna and to further miniaturize modern day electronics. UWB antennas are well suitable for such application. In literature, several different types of UWB antennas have been developed, however simple planar printed monopole antennas have received great attention for UWB systems [1]-[3], since they are low cost and feature simple structure, ease of fabrication, wide bandwidth, and omnidirectional radiation pattern. By integrating appropriate signal multiplexer to separate bands of interest for different sub-systems such as GPS, GSM, WLAN etc. high level of integration can be obtained while maintain independence of each subsystem. For such application, a directional filter multiplexer [4]-[7] can be used which allows for band separation and provides proper filtering of the band of interest. Basic concept of such system is presented in Fig. 1. An advantage of application of directional filters is that filter for each band is design separately and resulting multiplexer design is very flexible and can be modified without redesigning of entire structure. Moreover, such filters are low cost and require simple structure, compatible with one needed for planar UWB antenna realization.

In this paper we present new design of miniaturized coupled-line directional filter multiplexer. The small size has been achieved by miniaturization of its building block – directional filter combining quasi-lumped elements technique for transmission line sections miniaturization with miniaturization technique of directional couplers where coupled-line sections have been realized as a connection of tightly coupled and uncoupled lines. Theoretical analysis of the circuit has been presented. Moreover, an exemplary single directional filter multiplexer covering ISM 2.4 GHz has been developed and manufactured. The obtained measurement results proved that the proposed multiplexers are well suitable for band separation in UWB antenna multi-band, multi-purpose systems.

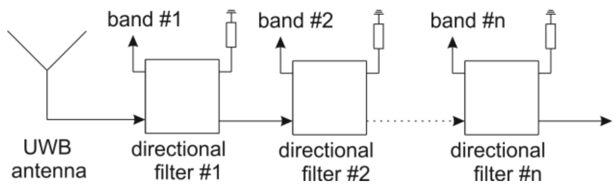

Fig. 1. General concept of a UWB antenna system with band separation using directional filter multiplexer.

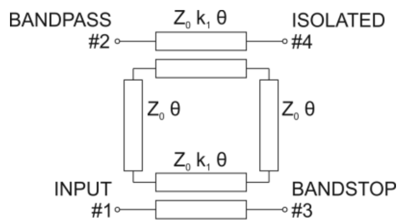

Fig. 2. Schematic diagram of a single-loop coupled-line directional filter. Band of interest is coupled from port #1 to port #2 while the rest of the input spectrum is transmitted to port #3. Electrical length of all lines equal 90° @ centre frequency f_0.

II. MINIATURIZED COUPLED-LINE DIRECTIONAL FILTERS

General concept of coupled-line directional filter realization is presented in Fig. 2. In this approach, two quadrature coupled-line directional couplers and two quarter-wave-long transmission line sections are utilized to create wave-long loop providing resonance at center frequency to couple band of interest from input port #1 to bandpass port #2 while creating bandstop at port #3. The bandwidth of such filter depends on the coupling level k of directional coupler while the quality factor depends from number of wave-long rings. Realization of such filter results however in relatively large occupied area due to

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wave-long loop. Therefore, it is worth to investigate the possibility of miniaturization of such a circuit.

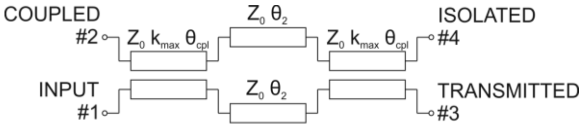

Fig. 3. Schematic diagram of a miniaturized single section directional coupler following the concept presented in [8].

One of the method of coupled-line directional coupler miniaturization is presented in [8], where directional coupler is designed as a connection of tightly coupled and uncoupled sections (see Fig. 3). In this case, two uncoupled lines are placed in the middle of a tightly-coupled sections. The short tightly-coupled section realizes the overall mutual capacitance and inductance that is needed for achieving the nominal coupling of the designed coupler while the uncoupled lines realize the missing self-capacitance and self-inductance of the initial coupler. The greater the difference between assumed nominal coupling level and maximum available one, the greater the miniaturization within method limits. Assuming nominal coupling k_{nom} and knowing maximum available coupling in selected dielectric structure k_{max}, assuming θ_{nom} = 90º, one can calculate required electrical lengths of tightly coupled and uncoupled lines [8]:

$$\theta_{cpl} = 0.5\frac{k_{nom}}{k_{max}}\frac{\sqrt{1-k_{max}^2}}{\sqrt{1-k_{nom}^2}}\theta_{nom} \tag{1}$$

$$A = arctan\left(\sqrt{1-k_{max}^2}cot(\theta_{cpl})\right) \tag{2a}$$

$$M = \frac{k_{max}^2}{\left(\sqrt{1-k_{max}^2}\right)cot^2(\theta_{cpl})+1} \tag{2b}$$

$$\theta_2 = A - 0.5arccos\left(\frac{-k_{nom}^2-k_{nom}^2M^2+2M}{2(1-k_{nom}^2)M}\right) \tag{3}$$

For miniaturization of transmission line sections, qauasi-lumped elements approach described e.g. in [9] can be utilized to ensure and maintain good electrical performance. In this approach, transmission line section is divided into n subsections and each subsection is realized using lumped elements. The required self-inductance and self-capacitance per subsection is determined based on the number of subsections n, overall phase shift introduced by the line θ_0 at f_0 and its characteristic impedance Z_0 from the following formulas:

$$L_{trl} = \frac{Z_0\theta_0}{2\pi f_0 n} \tag{4}$$

$$C_{trl} = \frac{\theta_0}{Z_0 2\pi f_0 n} \tag{5}$$

In order to physically realize the capacitive and inductive elements high impedance electrical short transmission lines and wide stubs serving as capacitors to ground are used.

Taking into account the above described analysis, the following procedure for the design of miniaturized directional filter can be proposed:

- First, based on the assumed bandwidth of the filter, coupling level of the coupled-line directional couplers composing filter has to be determined.
- Next, for selected dielectric structure, one can determine maximum available coupling level of the coupled lines. Following approach presented in [8] and knowing both desired and maximum coupling levels, electrical lengths of tightly-coupled and uncoupled transmission line sections are calculated.
- Following, miniaturized quadrature coupler having center frequency of the assumed filter is designed.
- Finally, two sections of transmission lines of appropriate electrical length creating inner loop of the filter are divided into n subsections and miniaturized with quasi-lumped elements technique.

III. Experimental Results

To verify the presented theoretical analysis an exemplary single directional filter multiplexer has been designed following the procedure presented in Section II. For proof-of-concept realization, an ISM 2.4 GHz band has been selected and center frequency f_0 = 2.45 GHz for bandpass output with 100 MHz wide 3-dB bandwidth have been assumed. To realize such a bandwidth, coupling coefficient of the coupled-line directional couplers of a single loop directional filter has been calculated to be k_{nom} = 0.34 (C = 9.37 dB), assuming system impedance Z_0 = 50 Ω. On the other hand, in the dielectric structure selected for the design of the circuit (see Fig. 4) maximum available coupling coefficient k_{max} = 0.74 (for Z_0 = 50 Ω). Required electrical lengths of coupled and uncoupled lines of directional coupler have been found based on (1)-(3): θ_{cpl} = 14.78° and θ_{trl} = 19.43°.

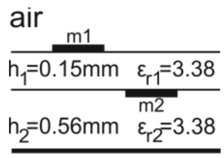

Fig. 4. Dielectric structure selected for the directional filter multiplexer design. Arlon 25N, 6 mil thick laminat has been bonded with 20 mil thick Arlon 25N laminate usig prepreg.

Moreover, the selected microstrip dielectric structure is on one hand well suitable for UWB antenna realization but on the other hand, directional couplers designed in such structure does not fulfill ideal coupled-line section conditions, since the inductive k_L and capacitive k_C coupling coefficients are unequal (in this case k_L = 0.719 and k_C = 0.763). In order to equalize those coefficients and improve the performance of directional filter, a compensation technique presented in [10] has been employed. The coupled-line coupler composing directional filter has been electromagnetically (EM) calculated and the results of EM calculations are presented in Fig. 5. Transmission line sections have been design as discussed in Section II and optimized. Initial values of inductance and capacitance for n = 4, assuming introduced phase shift θ_0 = 90º at f_0 to be realized are equal L_{trl} = 1.276 nH while C_{trl} = 0.51 pF. Layout of the designed miniaturized directional filter in comparison to the conventional one has been shown in Fig. 6, where appropriate compensating elements are visible. As seen, the designed filter is significantly smaller than the conventional one. It has to be underlined, that physical realization of the directional filter required the connection of signal lines to the coupled-line section, which introduced parasitic reactances deteriorating circuit's performance. Therefore, the final circuit has been optimized to minimize the performance deterioration due to parasitics. The designed exemplary single directional filter multiplexer has been manufactured and measured. A picture of the manufactured circuit is shown in Fig. 7, whereas a comparison between measured and ideal circuit calculated S-parameters is presented in Fig. 8.

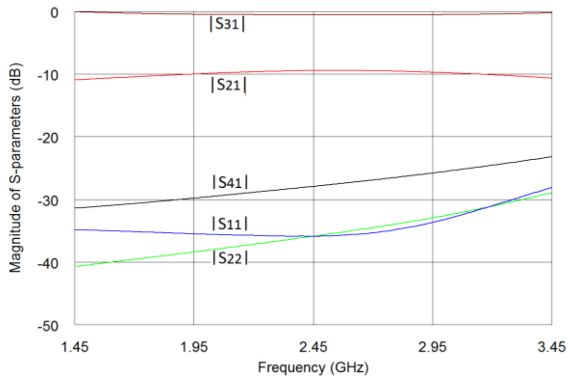

Fig. 5. S-parameters of the designed miniaturized coupled-line directional coupler. Result of electromagnetic calculations.

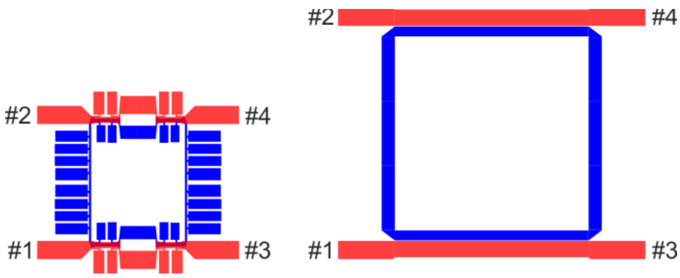

Fig. 6. Layout of the designed miniaturized single directional filter multiplexer composed of miniaturized directional coupler and miniaturized transmission line sections in comparision to classic approach (directional couplers are not compensated). Red – top layer m1, blue – bottom layer m2.

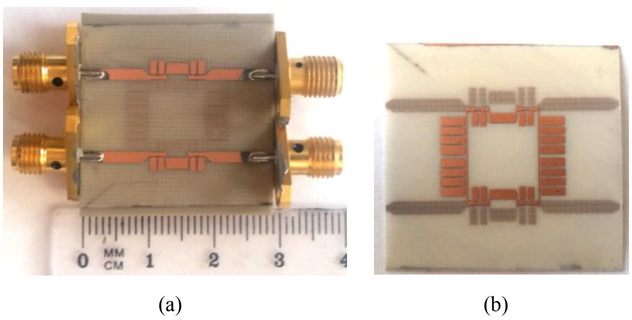

Fig. 7. A picture of the manufactured circuit. Top (a) and bottom (b) view. The overal size of the circuit equals 15.1 x 16.5 mm (not including input transmission lines).

As it can be seen, the exemplary manufactured circuit features good performance in terms of impedance match at all ports. Center frequency is slightly shifted to f_0 = 2.55 GHz while measured width of the passband equals 123 MHz. Isolation between bandpass and bandstop outputs at centre frequency equals I = 20 dB while measured insertion losses at center frequency are equal IL = 2.95 dB. The discrepancy between measured and ideal circuit calculated S-parameters is caused by losses as well as different than assumed thickness of the prepreg (upper and lower laminates have been bonded with prepreg using heat treated process) Variation in thickness resulted in slight change in phase shift introduced by miniaturized transmission lines and slight change of coupling coefficient of the coupler and what translated to slight shift of center frequency and slightly wider 3-dB band of operation.

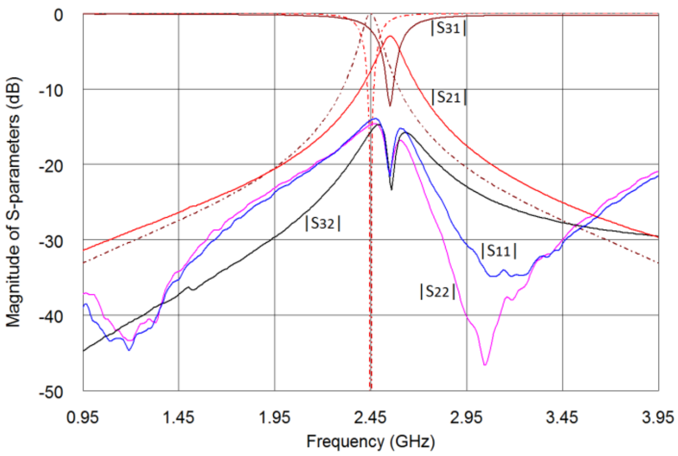

Fig. 8. Measured S-parameters of the manufactured directional filter (solid lines) in comparision with calculated ones for ideal circuit (dashed lines).

IV. Conclusion

The concept of a miniaturized coupled-line directional filter multiplexer in a multilayer microstrip technology has been presented. To achieve compact size of the directional filter, two miniaturization methods have been employed: for directional coupler miniaturization technique, in which the coupler is realized as a connection of tightly coupled and uncoupled lines, and for the transmission line quasi-lumped elements technique. Such an approach ensures at the same time good electrical properties and small size. The developed exemplary single directional filter multiplexer operates within ISM 2.4 GHz band, which makes it suitable for band separation in UWB antenna communication systems. Moreover, the proposed design is easily scalable for different frequency bands allowing the realization of multi-band multi-purpose system.

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