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A Frequency Triplexer for Ultra-wideband Systems Utilizing Combined Broadside- and Edge-coupled Filters

Magnus Karlsson, Pär Håkansson, *Member, IEEE*, and Shaofang Gong, *Member, IEEE*

Abstract—A fully integrated triplexer for multi-band ultra-wideband radio is presented. The triplexer utilizes a microstrip network and three combined broadside- and edge-coupled filters. It is fully integrated in a printed circuit board with low requirements on the printed circuit board process tolerance. Three flat sub-bands in the frequency band 3.1-4.8 GHz have been achieved. The group delay variation within each 500 MHz sub-band was measured to be around 1 ns. A good agreement between simulation and measurement was obtained.

Index Terms—Bandpass filter, Broadside-coupled, Edge-coupled, Frequency multiplexing, Triplexer, UWB

I. INTRODUCTION

The principle of frequency multiplexing, i.e., to combine the spectra from several ports into one wide spectrum has been proposed by several authors in different papers [1]-[12]. Suggestions about how to implement multiplexing or pre-selecting technique in ultra-wideband (UWB) systems have been made in [13]-[17]. We have recently proposed a frequency multiplexing technique in our study on ultra-wideband antennas [18] and transceivers [19], [20]. The uniqueness with our technique presented in this paper is that the triplexer is fully integrated in a printed circuit board using microstrips, resulting in a high performance but low cost solution for multi-band UWB. Frequency multiplexing techniques before us have used either waveguides or hybrids, having inherent difficulty for system integration and miniaturization.

UWB has gained popularity in recent years [21]-[29]. The interest for high speed and short range wireless-communication has been one of the major driving forces behind the UWB development [22]-[25]. Ever since the effort to achieve one sole UWB standard halted in early 2006, two dominating UWB specifications have remained as top competitors [28]. One is based on the direct sequence spread spectrum technique, supported by the UWB-forum [24], [27]-[28]. The other is based on the multi-band orthogonal frequency division multiplexing technique (Also known as “Wimedia UWB”, supported by Wimedia alliance) [25]-[26],

[29]. The multi-band specification divides the frequency spectrum into 500 MHz sub-bands (528 MHz including guard carriers and 480 MHz without guard carriers, i.e., 100 data carriers and 10 guard carriers). Three sub-bands are mandatory, centered at 3.432, 3.960, and 4.488 GHz, respectively [24]-[28]. Orthogonal frequency division multiplexing has the advantage of inherent robustness against gain, phase, and group delay variations [29], [30].

In multi-band systems, frequency multiplexers are used to replace switches. In reference [1] it is suggested to use directional filtering for multiplexing purposes, and a waveguide solution for operation in the X-band is presented. References [2]-[3] present a generalized manifold theory. Reference [4] presents an optimization algorithm for waveguide multiplexers. The algorithm is demonstrated with a 12-channel narrow-band waveguide multiplexer around 12 GHz. Reference [5] demonstrates a triplexer using dual-mode high-temperature superconductor thin-film filters and cryogenic circulators. Reference [6] shows a waveguide multiplexer solution using transmission lines, resonators and coupling capacitors. Reference [7] demonstrates procedures for minimizing the need of experimental correction when using computer-aided design. A waveguide duplexer and a four-channel multiplexer are designed using electromagnetic simulation. Reference [8] presents a lumped element and manifold microwave multiplexer using the high-temperature superconductor technology. Reference [9] presents a microstrip duplexer using band-stop filters. The band-stop filtering is achieved using open circuit stubs. Reference [10] presents both a duplexer and a triplexer for printed circuit board integration. However, the design still involves some lumped components and the sub-bands are fairly small, having large guard-bands. In reference [11] a duplexer using microstrips is presented, but requires structural redesign to extend the number of ports. Paper [13] proposes a stepped-impedance multiplexer for UWB and WLAN coexistence. In reference [14] a narrow-band four-channel multiplexer using open loop resonators for multi-band on-off keying UWB is demonstrated. Papers [15]-[16] show two channel-select multiplexers intended for UWB local oscillator signal selection, i.e., only one sub-band is active at the time. Microstrip and stripline filters have been presented in many shapes and realized in various structures [31]-[38].

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Our previous paper [18] proposes antenna parallelism using frequency multiplexing. The system is demonstrated with schematic level simulations. However, electromagnetically simulated edge-coupled filter and antenna models were used in the simulation. Our second paper [19] on the subject suggests to use the multiplexer from [18] as pre-select filter for a low noise amplifier from Maxim. In our third paper [20] the maximum theoretical data-rate limits of the proposed 11 sub-channel system using multiplexing techniques to combine the channels are studied. All our previous publications have been pre-studies of possible system implementations, whereas this paper presents a complete study of our three sub-band multiplexer (triplexer) for UWB systems. The triplexer in this paper is intended for mode 1 multi-band UWB that operates in three sub-bands between 3.1-4.8 GHz. The design is demonstrated using a conventional printed circuit board technology. The filters are not the main focus of this paper but a new type of combined broadside- and edge-coupled filters is presented and used in the triplexer. The filters were developed to ease printed circuit board integration, having an inherent advantage for this triplexer. Three filters with 500 MHz bandwidth at center frequencies of 3.432, 3.960 and 4.488 GHz are presented. One of the major challenges dealt with in this paper is the narrow guard-bands used by the multi-band UWB. The typical guard-band normally has a relative bandwidth of 10 % whereas as in this paper a guard-band of only 0.7 % is available.

II. OVERVIEW OF THE SYSTEM

All prototypes were manufactured using a four metal layer printed circuit board. Two dual-layer Rogers 4350B (RO4350B) boards were processed together with a Rogers 4450B (RO4450B) prepreg, as shown in Fig. 1. RO4450B prepreg is a sheet material (e.g., glass fabric) impregnated with a resin cured to an intermediate stage, ready for one stage printed circuit board bonding.

Table 1. Printed circuit board parameters

Parameter (Rogers 4350B)	Dimension
Dielectric height	0.254 mm
Dielectric constant	3.48±0.05
Dissipation factor	0.004
Parameter (Rogers 4450B)	Dimension
Dielectric height	0.200 mm
Dielectric constant	3.54±0.05
Dissipation factor	0.004
Parameter (Metal, Cu)	Dimension
Metal thickness, layer 1, 4	0.035 mm
Metal thickness, layer 2, 3	0.025 mm
Metal conductivity	5.8×10 ⁷ S/m
Surface roughness	0.001 mm

Table 1 lists the printed circuit board parameters, and Fig. 1 illustrates the stack of the printed circuit board. Metal layers 1 and 4 are thicker than metal layers 2 and 3 because the surface layers are plated twice (the embedded metal layers 2 and 3 are plated once).

Fig. 1. Printed circuit board structure.

A. Triplexer

Fig. 2a shows the schematic of the proposed triplexer. The network is realized with a microstrip technology. The triplexer consists of three series quarter-wavelength transmission lines, three bandpass filters, and three transmission lines for tuning of the filter impedance. The principle of operation is that each sub-band has a matched input impedance (50 Ω in this design) at the junction, but a high input impedance at the input of other sub-bands. The series transmission lines of three different quarter wavelengths provide a high impedance at the respective frequency band, i.e., preventing sub-band #1 signals to reach sub-band #2 and #3. The filter tuning lines at the junctions optimize the stop band impedance of each filter, to provide a high stop band impedance in the neighboring bands. Neighboring sub-bands are most critical to a sub-band since the band-pass filter has limited rejection close to its pass-band. The entire network is optimized together with the filters to achieve flat passbands and a symmetric performance between the sub-bands. Table 2 lists the specifications of the triplexer filters, where *length* is the length of the filter section, *width metal 1 and 2* are the widths of the layer 1 and 2 conductors in the broadside-coupled filter section, *conductor width* is the width of the edge-coupled filter section conductors, and *spacing* is the distance between the conductors. Note that the filters are symmetric, i.e., filter section 1 and 5 are equal, whereas 2 and 4 are also equal.

Table 2. Combined broadside- and edge-coupled filter specifications

Filter Parameter	Sub-band #1	Sub-band #2	Sub-band #3
Broadside-coupled filter section (1 and 5)			
Length (mm)	12.16	10.45	9.15
Width, metal 1 (mm)	0.87	0.87	0.87
Width, metal 2 (mm)	0.30	0.30	0.30
Edge-coupled filter section (2 and 4)			
Length (mm)	11.90	10.18	8.89
Conductor width (mm)	0.43	0.43	0.43
Spacing (mm)	0.16	0.26	0.26
Edge-coupled filter section (3)			
Length (mm)	11.86	10.15	8.85
Conductor width (mm)	0.44	0.44	0.44
Spacing (mm)	0.20	0.32	0.36

Fig. 2b shows a photo of the implementation. The size of the triplexer prototype is 53 x 60 mm. Three of the four soldered Sub-Miniature A (SMA) connectors are seen. SMA connectors mounted from the side connect the three input sub-bands. Port 2 is for sub-band #1 (3.432 GHz), Port 3 is for sub-band #2 (3.960 GHz), and Port 4 is for sub-band #3 (4.488 GHz). The fourth output connector (Port 1) is mounted

on the backside of the printed circuit board, i.e., only the soldered signal pin is seen. Moreover, it is seen that the prototype has a bend shape, which was done to achieve a more compact design. The design relies on impedance-controlled microstrip-lines, so the bending has no noticeable effect on the filter characteristic.

Fig. 2. Triplexer: (a) principle of the triplexer, and (b) photo of the implementation.

B. Filter structures

Two types of filter structures, i.e., combined broadside- and edge-coupled filters, and a conventional edge-coupled filters, are designed, simulated and measured. All filters have the same complexity, i.e., all filters are fifth order bandpass filters.

Combined broadside- and edge-coupled filter

Figs. 3a and 3b show the broadside-coupling and edge-

coupling, respectively. All implementations are made using microstrips. Fig. 3c shows the combined broadside- and edge-coupled filter. The start and the stop segments are placed on Metal layer 1 (see Fig. 3c), and the rest of the filter is placed on Metal layer 2. A fifth order bandpass filter, two orders from broadside-coupling and three orders from edge-coupling, are utilized.

Edge-coupled filter

Fig. 3d shows the traditional edge-coupled filter structure. The filter is positioned at metal layer 2, i.e., one of the embedded layers. A via and a small pad provide connectivity to Metal layer 1, not shown in Fig. 3d. SMA connectors are soldered to the pads on Metal layer 1.

Fig. 3. Filter structures: (a) broadside-coupling, (b) edge-coupling, (c) combined broadside- and edge-coupled filter, and (d) edge-coupled filter.

III. SIMULATED AND MEASURED RESULTS

Design and simulation were done with Advanced Design System (ADS) 2005A from Agilent technologies Inc. Measurements were done with a Rhode&Schwartz ZVM vector network analyzer.

A. Triplexer

Figs. 4a and 4b show the simulation and measurement results of forward transmission of the triplexer, respectively. A fairly flat passband (note the bandwidth mark at -3 dB) response is seen. The transmission line network is optimized together with the filters to achieve high blocking of neighboring bands. A good match between simulation and measurement results is seen. The complete multi-layer

structure was simulated with radiation characteristics enabled in ADS for the best accuracy. However, some limitations still exist in the simulations. The SMA connectors are not included, and moreover ADS Momentum (ADS electromagnetic simulator) does not take surface roughness into count. The simulated insertion loss is 1.3-1.6 dB, and measured insertion loss is 3.1-3.5 dB for the three sub-bands. All sub-bands have at least 500 MHz bandwidth at -3 dB from the top. Figs. 4c and 4d show the simulation and measurement results of return loss of the triplexer, respectively. Due to the narrow guard-band blocking of neighboring bands a smooth forward transmission was prioritized over low return loss, as seen in Figs. 4a-4d. The design freedom to achieve a low return-loss and smooth forward transmission is therefore limited. However, to use higher order than the fifth order band-pass filters would increase the design freedom but losses will increase. Figs. 4e and 4f show simulated and measured group delay, respectively. It is seen that for all the 500 MHz sub-bands the group delay is around 3.0 ns and the variation is approximately 1.0 ns within each sub-band. It will be seen later in Fig. 5 that the filters dominate the delay. Fig. 4g shows isolation between Ports 2-4. It is seen that the minimum isolation is 23 dB. The minimum isolation occurs at the boundary of the neighboring sub-bands, so in the three passbands the isolation is better than 23 dB. The isolation between the non-neighboring alternate sub-bands is 51 dB.

(a) Simulation of forward transmission.

(b) Measurement of forward transmission.

(c) Simulation of return loss.

(d) Measurement of return loss.

(e) Simulation of group delay.

(f) Measurement of group delay.

(g) Measurement of isolation between neighboring and alternate sub-bands.

(b) Measurement of forward transmission.

Fig. 4. Triplexer simulations and measurements: (a) simulated forward transmission with the passbands marked at -3 dB, (b) measured forward transmission with the passbands marked at -3 dB, (c) simulated return loss, (d) measured return loss, (e) simulated group delay, (f) measured group delay, and (g) measured isolation.

B. Combined broadside- and edge-coupled filter

The filters are 5th order bandpass filters. Figs. 5a and 5b show forward transmission simulation and measurement of the combined broadside- and edge-coupled filters. The three standalone combined broadside- and edge-coupled filter prototypes are labeled Broad-edge #1, #2, and #3, respectively. Simulated insertion loss is 0.8-1.2 dB, but measured insertion loss is 1.7-2.5 dB for the three sub-bands. All filters have at least 500 MHz bandwidth at -3 dB from the top as marked in the figure. Figs. 5c and 5d show the simulation and measurement results of return loss of the filters, respectively. An acceptable return loss of less than -6 dB in all sub-bands is seen. Figs. 5e and 5f show group delay simulation and measurement, respectively. The delay variation within the passband is less than 1.0 ns. Furthermore, the delay is near constant except at the passband edges.

(a) Simulation of forward transmission.

(c) Simulation of return loss.

(d) Measurement of return loss.

(e) Simulation of group delay.

(f) Measurement of group delay.

(b) Measurement of forward transmission.

Fig. 5. Broadside- and edge-coupled filter simulations and measurements: (a) simulated forward transmission with the passbands marked at -3 dB, (b) measured forward transmission with the passbands marked at -3 dB, (c) simulated return loss, (d) measured return loss, (e) simulated group delay, and (f) measured group delay.

C. Edge-coupled filter

As a comparison to the filter with combined broadside- and edge-coupling shown in Fig. 5, Figs. 6a and 6b show forward transmission simulation and measurement of the corresponding edge-coupled filters. These reference filters were made such that they are identical to the combined broadside- and edge-coupled filters except the start and stop segments. The three standalone edge-coupled filter prototypes are labeled Edge #1, #2, and #3, respectively. The performance of the edge-coupled filters is limited by the 0.113-mm minimum-spacing requirement from the manufacturer of the printed circuit board. The simulated insertion loss is 1.6-2.2 dB but the measured insertion loss is 3.3-3.9 dB for the three sub-bands. Large ripples in the passbands can be seen, and the bandwidth is thus limited. Figs. 6c and 6d show the simulation and measurement results of return loss of the filters, respectively. An unacceptable return loss of -2.5 to -3.0 dB in the sub-bands is seen. Figs. 6e and 6f show group delay simulation and measurement, respectively. The delay variation within the passband is related to the none-flat forward-transmission. A 1.5-ns delay variation and 1.0-ns ripple within the passband are seen. As compared to Fig. 5 it is apparent that this type of traditional edge-coupled band-pass filters has lower performance than our proposed filter with a combination of broadside- and edge-coupled structures.

(a) Simulation of forward transmission.

(c) Simulation of return loss.

(d) Measurement of return loss.

(e) Simulation of group delay.

(f) Measurement of group delay.

Fig. 6. Edge-coupled filter simulations and measurements: (a) simulated forward transmission with the passbands marked at -3 dB, (b) measured forward transmission with the passbands marked at -3 dB, (c) simulated return loss, (d) measured return loss, (e) simulated group delay, and (f) measured group delay.

IV. DISCUSSION

In general, a good agreement was seen between simulated and measured results. However, for the triplexer and the filter prototypes the measured insertion loss was approximately 1.5 dB more than the simulated one. A slightly downward shift in frequency is also seen, i.e., a constant error of 2.5 %. The frequency shift is due to the fact that the simulated electrical length of the resonator differs from the measured one, i.e., the simulated phase velocity is higher than the measured one. The higher insertion loss from the measurements can be explained by the surface roughness that is not included in the simulations because ADS does not support that. It is a known fact that surface roughness increases insertion loss [39], [40]. From [39] the insertion loss due to roughness for an equivalent microstrip-line can be estimated to be from 0.06 to 0.10 dB/cm within the 3.1-4.8 GHz frequency-band. Considering the different sub-band route lengths the minimum additional insertion-loss due to surface roughness is estimated to be 0.60, 0.64, and 0.72 dB, for sub-band #1, #2, and #3, respectively. Moreover, some additional insertion-loss may come from reflections caused by the SMA connectors soldered on the triplexer. Furthermore, the isolation between sub-bands was prioritized over the reflection during the design process due to the tough bandwidth conditions, i.e., 500-MHz-wide sub-bands with only 28-MHz-wide guard-bands (a relative bandwidth of 0.7 % at 4 GHz).

The group delay variation was measured to be about 1 ns within each sub-band. In pulsed multi-band systems this group delay variation might cause degradation of system performance. However, in orthogonal frequency division multiplexing systems the group delay impact on the system level performance should be marginal [29].

To achieve strong coupling with an edge-coupling technique, the minimum line-spacing is required. Designs with the minimum line-spacing are not robust against fabrication process variations. Broadside-coupling can replace any edge-coupled filter-segment with strong coupling, i.e., filter

segments with narrow spacing. The optimal spacing between edge-coupled filter segments is dependant of the relative bandwidth (passband relative to the center-frequency), but in general it is the first and the last segments that have the smallest spacing. It should be mentioned that other filter optimization techniques might improve the edge-coupled filter as well, but the combined broad-edge solution presented in this paper shows one possibility to not only enhance performance but also make the integration easier. By using the broadside coupling, the printed circuit board tolerance requirement on the minimum spacing for the whole triplexer is relieved. Thus, the triplexer can be integrated into a printed circuit board without specific requirements on the printed circuit board process tolerance. Therefore, this triplexer can be integrated into a conventional four metal layer printed circuit board with low cost.

V. CONCLUSION

A fully integrated planar triplexer using microstrips for multi-band UWB has been presented. Three flat sub-bands in the frequencyband 3.1-4.8 GHz for multi-band UWB have been achieved. The triplexer can be integrated into a printed circuit board using a commercial process technique at low cost, even though the guard-band has only a relative bandwidth of 0.7 % between the three sub-bands. The triplexer uses three filters with a combined broadside- and edge-coupled structure. It is verified that this kind of combined broadside- and edge-coupled filters has higher performance than that of conventional edge-coupled filters.

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