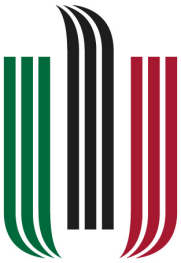

AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY

FIELD OF SCIENCE: Engineering and Technology

SCIENTIFIC DISCIPLINE: Automation, Electronic and Electrical Engineering

SUMMARY OF DOCTORAL THESIS

Microwave directional couplers' design with the use of planar quasi-TEM transmission line sections. Analysis, experimental investigation and applications

Author: Robert Smolarz

Supervisor: Prof. Sławomir Gruszczyński

Completed in:
Faculty of Computer Science, Electronics and Telecommunications
Institute of Electronics

Krakow, 2022

AGH

AKADEMIA GÓRNICZO-HUTNICZA
IM. STANISŁAWA STASZICA W KRAKOWIE

DZIEDZINA NAUK INŻYNIERYJNO-TECHNICZNYCH

DYSCYPLINA AUTOMATYKA, ELEKTRONIKA I ELEKTROTECHNIKA

AUTOREFERAT ROZPRAWY DOKTORSKIEJ

Projektowanie mikrofalowych sprzęgaczy kierunkowych w technice linii transmisyjnych quasi-TEM. Analiza, projektowanie i badania eksperymentalne.

Autor: Robert Smolarz

Promotor: Prof. Sławomir Gruszczyński

Praca wykonana:
Wydział Informatyki, Elektroniki i Telekomunikacji
Instytut Elektroniki

Kraków, 2022

MICROWAVE DIRECTIONAL COUPLERS' DESIGN WITH THE USE OF PLANAR QUASI-TEM TRANSMISSION LINE SECTIONS. ANALYSIS, EXPERIMENTAL INVESTIGATION AND APPLICATIONS

Abstract

Modern radio communication and radiolocation systems have to fulfill ever demanding requirements. Cellular network standards such as LTE Advanced or 5G are based on operation across a broad frequency band. It is also important that wireless devices become increasingly efficient and miniaturized. These requirements can be addressed by designing integrated circuits using the strip transmission line technique in which a quasi-TEM wave propagation appears. From a practical point of view, such circuits are manufactured using *printed circuit board* (PCB) technology or on special ceramic or semiconductor substrates with *monolithic microwave integrated circuit* (MMIC) technology. In both cases, the integration of active and passive systems within one device or functional block becomes simple in terms of simulation and fabrication. However, such networks feature insertion and reflection losses that appear at the connections of mismatched circuits operating in the microwave frequencies. Another issue is related to the miniaturization aspect, which is especially crucial for passive components designed using the MMIC technique. In the case of components consisting of transmission lines (e.g. directional couplers), the geometry of the designed circuitry can exceed the size of a single integrated circuit, which is defined by a chosen technological process.

The scope of this dissertation focuses on three main aspects related to microwave directional couplers. The first concerns the possibility of improving the properties of couplers composed of coupled-line sections designed in both PCB and MMIC technologies. This work discusses the methods of even and odd phase velocity compensation in symmetrical structures, as well as the equalization of inductive and capacitive coupling coefficients in asymmetric structures. Such approaches improve the electrical performance of the couplers in terms of obtained directivity, isolation and return losses. The author proposed the utilization of such methods in single-ended and differentially-fed directional couplers. Furthermore, an investigation on the reduction of total losses in two- and four-coupled-line section has been conducted.

The second aspect is focused on the development and analysis of impedance-transforming directional couplers operating in narrow and wide frequency bandwidths. In well-known solutions, the impedance of all of the coupler's ports is the same and is equal to the standardized value of 50 Ω. In cases where such a coupler has been connected with a component that has a different impedance, an effect called impedance mismatch is observed. Such an issue has a direct influence on return loss increase, and therefore on the degradation of the total performance of the circuit. In such cases, the use of impedance-transforming directional couplers is desirable and enables the significant improvement of circuit parameters. First, a reduction of the return losses between the ports of the elements is obtained. Second, the overall size of the designed circuit can be reduced because additional matching circuits are no needed. In this work, studies related to the impedance-transforming hybrid couplers based on rat-race and tandem topologies operating in narrow and broad operational bandwidths is presented. In comparison

to well-known solutions, the impedance-transformation ratio is increased. Moreover, an enhancement of the bandwidth in the rat-race coupler is also obtained.

The last topic discussed in the dissertation focuses on the utilization of the developed directional couplers in complex, monolithic applications based on gallium arsenide. As part of the work, two miniaturized hybrid couplers in a single-ended and a differentially-fed branch-line topology have been proposed. The couplers have been used in the design of a monolithic sensor intended for measurements of material dielectric permittivities and in a monolithic balanced differentially excited amplifier, which has been designed for the purposes of this dissertation. The third of the designed chips is a monolithic *frequency-modulated continuous-wave* (FMCW) radar front end operating in the automotive frequency band, in which a previously designed compensated three-coupled-line section coupler was utilized.

The developed design methods and circuits have been experimentally verified by measurements of the fabricated structures. In each of the proposed directional couplers, the performance has been improved in relation to the existing solutions. In addition, the last chapter confirms the applicability of the developed monolithic solutions in monolithic microwave integrated circuits.

PROJEKTOWANIE MIKROFALOWYCH SPRZĘGACZY KIERUNKOWYCH W TECHNICE LINII TRANSMISYJNYCH QUASI-TEM. ANALIZA, PROJEKTOWANIE I BADANIA EKSPERYMENTALNE.

Streszczenie

Wymagania stawiane przed nowoczesnymi systemami radiokomunikacyjnymi i radiolokacyjnymi są coraz wyższe. Standardy sieci komórkowych takie jak LTE Advanced czy 5G opierają swoje działanie na pracy w szerokim paśmie częstotliwości. Ważne jest też, aby urządzenia radiowe osiągały coraz większą sprawność i większy stopień zminiaturyzowania. Założenia te można spełnić projektując układy zintegrowane wykorzystujące technikę linii paskowych, w których występuje zjawisko propagacji fali quasi-TEM. Z praktycznego punktu widzenia, są to obwody wykonywane na laminatach w tzw. technologii PCB (ang. *Printed Circuit Board*) lub na specjalnych podłożach pół ceramicznych, półprzewodnikowych w technologii monolitycznej. W obu tych przypadkach, zintegrowanie układów aktywnych z pasywnymi w obrębie jednego urządzenia czy też bloku funkcjonalnego staje się proste pod względem symulacji oraz wykonania. Niestety dużym problemem są straty wtrąceniowe oraz odbiciowe, które pojawiają się na połączeniach niedopasowanych układów pracujących w paśmie mikrofalowym. Inną problematyczną kwestią jest miniaturyzacja układów pasywnych projektowanych szczególnie w technice monolitycznej. W przypadku realizacji komponentów składających się z linii transmisyjnych (np. sprzęgacze kierunkowe), geometria projektowanego układu może być większa niż rozmiar pojedynczego układu scalonego, który jest zdefiniowany przez dany proces technologiczny.

Zakres niniejszej rozprawy doktorskiej skupia się na trzech głównych aspektach związanych z mikrofalowymi sprzęgaczami kierunkowymi. Pierwszy z nich dotyczy możliwości polepszenia właściwości sprzęgaczy zbudowanych z sekcji sprzężonych linii transmisyjnych wykonanych w technologii PCB i monolitycznej. W ramach pracy omówiono metody kompensacji prędkości fazowych rodzajów parzystego i nieparzystego (struktury symetryczne) oraz indukcyjnego i pojemnościowego współczynnika sprzężenia (struktury asymetryczne), które mogą być zastosowane w sprzęgaczach o pobudzeniu klasycznym (tzw. *single-ended*) lub różnicowym. Zaproponowano również rozwiązania pozwalające na projektowanie dwu- i cztero- paskowych sekcji sprzężonych o zredukowanych stratach całkowitych (sprzęgacz w topologii Langego).

Drugim aspektem jest opracowanie oraz analiza sprzęgaczy kierunkowych pozwalających na transformację impedancji w wąskim i szerokim paśmie pracy. W klasycznych rozwiązaniach, impedancja wszystkich wrót sprzęgacza jest taka sama i w większości wypadków równa 50 Ω. W przypadku, gdy do tak zaprojektowanego sprzęgacza zostanie podłączony układ o innej impedancji (np. układ nieliniowy w postaci wzmacniacza), następuję tzw. niedopasowanie impedancyjne i degradacja parametrów całego obwodu poprzez powstałe straty odbiciowe. W takim przypadku, zastosowanie sprzęgaczy kierunkowych transformujących impedancję jest wskazane i pozwala na znaczącą poprawę właściwości układowych. Po pierwsze następuje redukcja wspomnianych strat odbiciowych między wrotami elementów. Po drugie, rozmiary projektowanego obwodu mogą zostać znacząco zmniejszone, ze względu na brak dodatkowych obwodów dopasowujących. W niniejszej pracy przedstawiono opracowane wąskopasmowe i szerokopasmowe sprzęgacze hybrydowe transformujące impedancje, w których znacząco zwiększono tzw. współczynnik transformacji impedancji oraz nastąpiło zwiększenie pasma operacyjnego. Układy

te zostały oparte o topologię pierścieniową (tzw. *rat-race*) oraz tandemową zbudowaną z sekcji linii sprzężonych.

Ostatni, poruszony temat skupia się na użyciu opracowanych sprzęgaczy kierunkowych o polepszonych właściwościach do zastosowań w bardziej złożonych układach wykonanych w technice monolitycznej bazującej na arsenku galu. W ramach pracy zaproponowano dwa zminiaturyzowane sprzęgacze hybrydowe w topologii gałęziowej (tzw. *branch-line*) o pobudzeniu: single-ended i różnicowym. Zaproponowane układy zostały następnie wykorzystane kolejno w projekcie monolitycznego sensora do badań np.: przenikalności dielektrycznej materiałów oraz w monolitycznym zrównoważonym wzmacniaczu pobudzanym różnicowo, który został zaprojektowany na potrzeby niniejszej rozprawy. Trzecim z zaprojektowanych układów jest monolityczny układ radaru z ciągła falą modulowaną częstotliwościowo FMCW (ang. *Frequency-Modulated Continuous-Wave Radar*) pracujący w paśmie przewidzianym dla branży automotive w którym wykorzystano wcześniej zaprojektowany skompensowany sprzęgacz trójpaskowy zbliżeniowy.

Opracowane metody projektowe oraz układy zostały zweryfikowane eksperymentalnie poprzez pomiary wykonanych układów lub symulacje (tak stało się jedynie w przypadku monolitycznego wzmacniacza zrównoważonego). W każdym z zaproponowanych sprzęgaczy kierunkowych stwierdzono poprawę parametrów względem znanych już rozwiązań. Dodatkowo, ostatni rozdział w którym to zweryfikowano aplikacyjność potwierdza możliwość implementacji opracowanych rozwiązań monolitycznych w monolitycznych mikrofalowych układach scalonych.

1. Aim of the Thesis

The thesis presents design methodologies, analysis and results related to the directional couplers utilized in planar PCB and monolithic technologies. To design high-performance component, the main issues have been collected, and formulated into the following theses:

1. The equalization of inductive and capacitive coupling coefficients in asymmetric planar low-loss directional couplers is possible and can improve directivity.
2. The equalization of inductive and capacitive coupling coefficients increase directivity in monolithic directional couplers.
3. The modification of classic directional coupler topologies allows impedance transformation in broader operational bandwidths and increase impedance transformation ratio.
4. High-performance directional couplers may be utilized as components of radio frequency circuits designed using the monolithic technology.

Each of the presented goals is discussed in four chapters showing detailed analysis, and experimental results of the designed solutions.

2. Summary

In this thesis, an investigation on the improved directional couplers designed in PCB and monolithic technologies has been presented. The thesis contains three main topics which are related to the design of high-performance directional couplers, impedance-transforming couplers and the applicability of the proposed couplers in monolithic complex circuits. Several novel approaches have been proposed together with appropriate numerical analysis which have been verified by simulations and physical realizations.

The author investigated the possibility of improvement of the single-ended and differentially-fed directional couplers by utilizing the capacitive compensation method and appropriate stack-up stratification. The compensation method has been used in the low-loss suspended microstrip technique for two different cases: a two-coupled-conductor section in which quasi-lumped capacitors have been added and a four-coupled-conductor Lange structure in which compensation has been achieved by properly chosen substrate stack-up. It has been proven than the proposed approaches improves the electrical performance of the couplers, which can be noticed in the increase of isolation and return losses. Moreover, a modified compensation method based on smaller amount of additional capacitances has also been used in monolithic technology, where three topologies were realized in the gallium arsenide process.

The improvement of the differentially-fed couplers realized in the homogeneous and inhomogeneous medium has been also studied. The author proposes a novel topology of a differentially excited tandem coupler designed using homogeneous stratification to increase coupling factor. Furthermore, symmetric and asymmetric two-coupled-conductor sections have been realized in inhomogeneous structures. In the first case, an investigation on the equalization of modal dielectric permittivies by a proper ratio between layer thicknesses of the stripline structure was conducted. It has been proven that, the optimal values of electrical parameters can be achieved for case, where thickness ratio between the inner layer and the outer ones equals two. In the second case, an additional compensation layer was proposed to equalize the capacitive and inductive coupling coefficients of the coupler.

Regarding impedance-transforming couplers, the author proposed three novel approaches based on impedance-transforming tandem-connected, narrow and broadband versions of rat-race couplers. It has been shown that tandem topology can achieve an impedance-transforming ratio greater than in the classic case, where $R = 2$. Moreover, it has been proven that such a coupler has a similar frequency response as a two-section structure. As previously mentioned, the author also investigated the directly-connected hybrid couplers and the possibility of their application as impedance-transforming components. It has been shown, that a narrowband version of such a coupler features such an ability without any additional elements. Moreover, to enhance operational bandwidth, the rat-race coupler needs only two coupled-line

sections connected to the opposite ports of the coupler.

Additionally, the thesis shows the implementation of the proposed improved directional couplers in complex monolithic circuits such as: monolithic sensor systems, balanced amplifiers and FMCW radar front-ends. For the purposes of this thesis, the author designed a differentially-fed balanced amplifier consisting of the novel miniaturized branch-line coupler. The single-ended branch-line coupler designed using a lumped-elements technique has been utilized in a monolithic sensor which is composed of a sensing part integrated with measurement circuitry based on a five-port correlator. In the FMCW radar front-end, the compensated three-strip coupled-line directional coupler has been utilized to increase the overall electrical performance of the chip. Both circuits have been designed in the gallium arsenide PH25 process provided by UMS.

The original achievements of the author presented in this thesis can be summarized as follows:

- the development of single-ended low-loss compensated directional couplers;
- the development of multi-strip low-loss compensated coupled-line directional couplers;
- the development of high-performance monolithic coupled-line directional couplers;
- the development of differentially-fed tandem-connected directional couplers in the homogeneous structure;
- the development of differentially-fed symmetric and asymmetric directional couplers based on the inhomogeneous stratifications;
- the development of impedance-transforming tandem-connected directional coupler;
- the development of impedance-transforming narrowband and broadband rat-race couplers designed using microstrip and suspended microstrip (low-loss version) techniques;
- the development of a monolithic integrated sensor with built-in calibration capability;
- the development of a miniaturized monolithic branch-line coupler;
- the development of a monolithic differentially-fed balanced amplifier based on a gallium arsenide substrate;
- the development of a monolithic FMCW radar front-end operating at the 24 GHz center frequency based on a gallium arsenide substrate.

Further research will be focused on the realization of high-performance broadband combined amplifiers such as multiport networks, balanced and unbalanced topologies, designed using PCB and monolithic technologies. In such circuits, directional couplers are utilized as one of the main components and have a direct influence on the entire performance of the amplifier. The preliminary results presented in the dissertation shows that one of the developed couplers can be utilized in monolithic amplifiers based on gallium arsenide, and features good electrical-performance. However, such a solution is not

suitable for high-power applications. Thus, the author plans to include gallium nitride processes in future research.

Another promising direction of further research can be found in the design of monolithic low-power consumption radars and sensors intended for the measurement of biological samples. The preliminary results presented in the literature and the thesis shows that such circuits can be designed in monolithic processes. However, further development is required in terms of improved performance.

The most important publications

JOURNAL PAPERS FOCUSED DIRECTLY ON THE DISSERTATION'S SUBJECT:

- **R. Smolarz**, K. Staszek, K. Wincza, and S. Gruszczynski "A 24 GHz microwave sensor with built-in calibration capability designed in MMIC technology," *IEEE Access*, vol. 9, pp. 31513-31524, February 2021.
- **R. Smolarz**, K. Wincza, and S. Gruszczynski "Modal phase velocity compensation in multilayer differentially fed directional couplers," *Microwave and Optical Technology Letters*, vol. 62, no. 5, pp. 1882-1887, May 2020.
- S. Gruszczynski, **R. Smolarz**, and K. Wincza, "Differential Bi-Level Microstrip Directional Coupler with Equalized Coupling Coefficients for Directivity Improvement," *Electronics*, vol. 9, no. 4, pp. 547-, March 2020.
- S. Gruszczynski, **R. Smolarz**, C. Wu, and K. Wincza, "Monolithic Miniaturized Differentially-Fed Branch-Line Directional Coupler in GaAs Monolithic Technology," *Electronics*, vol. 9, no. 3, pp. 446-, March 2020.
- S. Gruszczynski, **R. Smolarz**, and K. Wincza, "Realization of high-performance broadband quadrature directional couplers in UMS PH25 technology," *Electronics*, vol. 8, no. 12, pp. 1520-, December 2019.
- **R. Smolarz**, K. Wincza and S. Gruszczynski, "Impedance transforming rat-race couplers with modified Lange secton," *Journal of Electromagnetic Waves and Applications*, vol. 32, no. 8, pp. 972–983, May 2018.
- **R. Smolarz**, K. Wincza and S. Gruszczynski, "Impedance transforming tandem couplers with increased bandwidth and transformation ratio," *IEEE Microwave and Wireless Components Letters*, vol. 28, no. 4, pp. 299–301, March 2018.
- **R. Smolarz**, K. Wincza and S. Gruszczynski, "Design of low-loss durectional couplers with compensated coupled-line sections in suspended microstrip technique," *International Joutnal of RF and Microwave Computer-Aided Engineering*, vol. 27, no. 8, October 2017.

CONFERENCE COMMUNICATES FOCUSED DIRECTLY ON THE DISSERTATION'S SUBJECT:

- **R. Smolarz**, K. Wincza, and S. Gruszczynski, "Design of 3-dB Differentially-Fed Tandem Directional Couplers," in *Proc. of the IEEE MTT-S International Wireless Symposium (IWS)*, Guangzhou, China, May 2019, pp. 1–3.
- **R. Smolarz**, K. Wincza, and S. Gruszczynski, "Broadband low-loss impedance transforming rat-race coupler in suspended microstrip technique," in *Proc. of the 22nd International Microwave and Radar Conference (MIKON)*, Poznan, Poland, May 2018, pp. 291–293.
- K. Janisz, **R. Smolarz**, A. Rydosz, K. Wincza, and S. Gruszczynski, "Compensated 3-dB lange directional coupler in suspended microstrip technique," in *Proc. of the 7th IEEE International Symposium on Microwave, Antenna, Propagation, and EMC Technologies (MAPE) 2017*, Xi'an, China, October 2017, pp. 289–291.