A Fully Differential Single-Stage Four-way mmWave Power Combiner for Phased Array 5G Systems

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***Abstract*—This paper presents design of a fully differential four-way power combiner for receiver phased array applications. Depending on the system requirements several techniques for combining receiving channels from antenna inputs, for example, Wilkinson Power combiners, current summing power combiners and transformer-based power combiners are utilized. In this work, we show a design procedure of a four-way transformer based current summing power combiner with wideband response from 23 and 45 GHz frequencies. A single stage power combiner shows a simulated insertion loss of 1.5 to 3 dB, compared to Wilkinson power combiner's loss of 3.6 to 6 dB. Isolation between the channels is -14 dB. The proposed combiner and Wilkinson combiner consume area of 0.101 mm^2 and 1.034 mm^2, respectively. Both combiners are designed using 45 nm CMOS SOI process technology.**

Keywords—CMOS SOI, RF, mmWave, phased array, receiver, phased array, power combiner, wilkinson, 5G

I. INTRODUCTION

Phased array systems are getting more attention of wireless communication industry, because of its inherent capabilities of beamforming and improvement in signal-to-noise ratio (SNR) of the radio link. Some mm-wave frequency bands have been proposed and finalized for 5G communication systems due to the availability of wide range of bandwidth (> 1GHz), at 24GHz, 28GHz and 38 GHz bands [1], [2]. Depending on the location of the phase shifter in the signal chain and/or combining node of multiple elements, different kinds of beamforming techniques are used in phased array systems, e.g. RF Beamforming, LO beamforming, intermediate frequency (IF) beamforming, or hybrid beamforming. In mmWave frequency systems LO routing becomes more complex, and therefore phase shifting and combining is more commonly implemented in the RF/mmWave path. Signal combining or splitting in a phased array transceiver systems is also becoming a topic of interest for future research.

Signal combining network design for phased array systems has very specific requirements about isolation and loss. As the preceding stage of the combiner in a typical phased array receiver systems is a phase shifter, which has multiple switching states, eventually, which can create problems of loading input stage of the subsequent block elements and neighboring signal chains. Therefore, there should be enough isolation between the combining ports, which can mitigate the switching effect between phase shifter states. Recently, different types of signal combiners are used in mmWave phased array systems, for example, Wilkinson power combiners, current summing signal combiners and transformer based signal combiners. In [1], a current summing technique is presented at 15 GHz 4 x 1 phased array system, using Gilbert cell type active transconductance stages to convert input voltage signal into current and then output currents are summed using a narrowband LC tank load. The transconductance stage also provides enough isolation between the combining ports. A wideband transformer load is utilized in [2] to add currents of two elements in a single stage of combining towards implementation of an 8 x 1 element phased array receiver system. However, the current-combining based signal combiners in [1] to [3] are based on transconductance stages, and can bring additional limitations for non-linearity of the system.

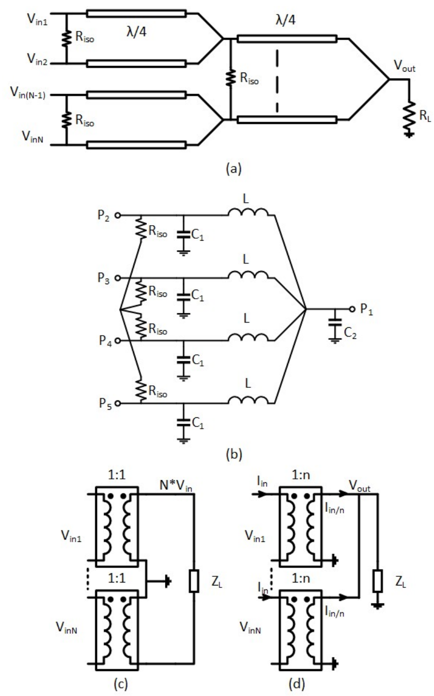

Fig 1: Power combining techniques, (a) Wilkinson power combiner, (b) Wilkinson power combiner implemented with lumped elements, (c) Transformer based voltage combiner, (d) Transformer based current combiner

A passive power combing network technique using tree configuration of three Wilkinson power combiners, is utilized in [4] to simultaneously combine four signal paths. A 4-to-1 differential power combiner network based on Wilkinson power combiners, is presented in [5] at 28 GHz. Both techniques presented in [4] and [5] consume a large chip area. A lumped element-based Wilkinson power splitter at 60 GHz is demonstrated in [6], where a differential network of two transformers is utilized to realize the Wilkinson power splitter. This design is more compact than the transmission line (TL) based Wilkinson splitter/combiner, however, it still requires a 3-stage network for a 4-to-1 combining. In [7], a transformer based 4-to-1 power combiner is presented to combine the four outputs of a power amplifier to a single output. However, this is low frequency work, i.e. 3GHz.

In this work, we present a single stage and fully differential, 4-to-1 transformer based power combiner/splitter for phased array systems operating at 23 GHz to 45 GHz in 45nm CMOS SOI process technology. A TL based Wilkinson combiner is also designed for the comparison. After introduction, the paper is organized such that different power combiner techniques are discussed in section II, while design of a single stage 4-to-1 power combiner is presented in section III with results in section IV. paper is concluded in section V.

II. Power Combiners

A. Wilkinson Power Combiner

Classical Wilkinson power combiners/dividers (WPC) are common for mm wave applications. For a particular frequency, a combination of quarter wave length (λ/4) TLs are used to design WPC, as shown in Fig. 1 (a). An isolation resistor is required to improve the isolation between the combining channels. As the λ/4 TLs are designed for a single frequency, WPC are used for narrowband solutions. However, multiple stages can be cascaded to achieve wideband response at the expense of area and insertion loss. Due to the large area of TL based power combiners in CMOS, lumped element-based WPC are also used. As the number of channels to be added are increased, the routing for isolation resistors also becomes complicated, as shown in Fig 1 (b).

B. Current Summing Power Combiner

In direct current combining technique, outputs of all elements combine directly at summing node as shown in [2]. Typically, inside CMOS phased array receiver the output of the array element is in voltage domain. Transconductor is used for V to I conversion. Current combining needs low impedance node. The load at summing node could be resistive, simple resonator or transformer load for wide bandwidth [2]. In addition, transformer converts the signal from I to V. However, the summing node is sensitive to parasitics, when more than two stages are combined. In that case, it is better to combine two array elements at once [2]. This strategy leads to high power consumption and linearity of phased array receiver becomes a challenge in case of high-power input signal. A block diagram of a current summing active combining network of N number of elements is shown in Fig. 2.

C. Transformer-Based Power Combiner

Transformers can be used for combining N number of input signals from primary coils to N secondary coils, which can be connected in either a series or parallel combinations. Two types of transformer-based combiners are discussed for power amplifier applications, in [8], i.e. series or voltage based combining and parallel or current based combining (see Fig. 1 (c) and (d)). In a series or voltage combining technique, secondary coils are connected in series, which transforms the load impedance of the preceding amplifier at primary coil, to values less than the load impedance at the secondary side, i.e. ZL. This reduction in primary side impedance results in higher power delivery to ZL. However, as the number of stages to combine grows, the load impedance of preceding amplifier reduces to very lower values, which results in increased sensitivity to losses and less isolation between different channels.

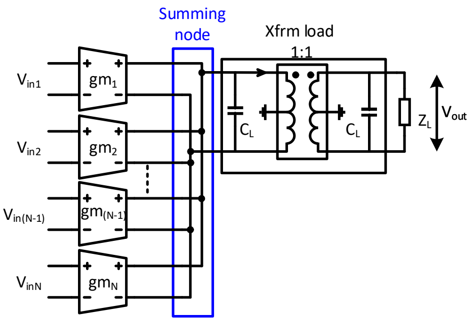

Fig 2: Current summing active combining

For some phased array receiver systems, cartesian phase shifter is the preceding stage for combiner [1]. Which includes variable gain amplifier (VGA) to provide variable magnitude for required phase shift and 90-degree phase in one branch. By switching to different states of VGA, changes the load impedance. Change in output load of VGA causes load variation between array elements. Which leads to beam pointing error. For an *n*-way combiner, current combiner transformers with a turns ratio 1:1, load impedance of the secondary coil is *n* times the input impedance of a primary coil as given by (1). For a 50 Ohm load impedance, *m*-way current combiner would transform to *n* times Z_{in}, which is 200 Ohms for a *4*-way combiner. However, if the turns ratio of combining transformers is 1:*m* (*m*>1), the transformation of Z_l to Z_{in} are given by (2). For a 50 Ohm Z_l, *4*-way current combiner would transform 50 Ohm Z_l into 50 Ohm Z_{in}.

$$Z_{in} = Z_l \times n \quad (1)$$
$$Z_{in} = Z_l \times \frac{n}{m^2} \quad (2)$$

Current combining technique is less prone to parasitics because the output impedance of preceding amplifier increases with the increase in number of channels. However, power delivered to load decreases as the load impedance becomes lower than the input impedance, which can be relaxed by using secondary winding turn ratio more than 1:1. Higher output impedance transformation of the preceding VGA, can withstand at higher parasitic components improves isolation between different channels. Fig. 3 shows the implementation of current and voltage combining for two elements using transformers with turns ratio 1:2.

III. SINGLE-STAGE 4-TO-1 POWER COMBINERS

Two 4-to-1 passive combiners are designed and simulated using 45 nm CMOS SOI technology process. The technology offers two ultra-thick copper metal layers together with aluminum layer for better Q values of passive structures for millimeter-wave frequency designs. In addition, SOI process inherit high resistive substrate properties, which ensure high quality factor for passive designs. Fig. 4 presents schematic of a single-stage 4-to-1 current combining transformer-based power combiner. Network is designed to be matched with 50 Ohms over the frequency range of 23 GHz to 45 GHz.

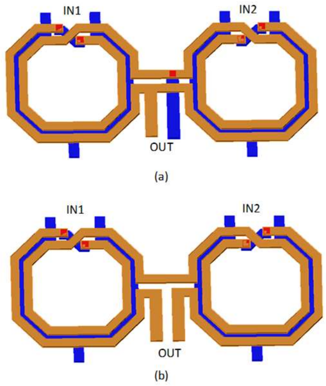

Fig 3: Transformer based combining techniques, (a) Current combining, (b) Voltage combining

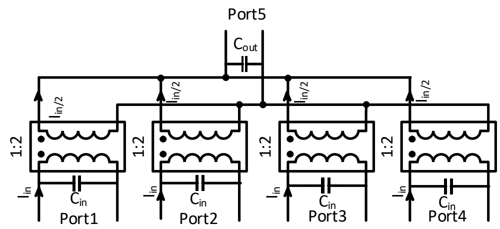

Fig 4: Sechematic diagram of a 4 x 1 transformer based current combiner network

Metal stack is shown in Fig. 5(a). From (2), it has been concluded that to match a 50 Ohm input and output impedance, 1:2 turn transformer is required. Therefore, four transformers each with turn ratio 1:2 are used to combine four differential inputs. Primary winding of each transformer is drawn using thick metal m7 from the metal stack, while thick metal m8 is used to draw two turns secondary winding. A cross-connect is implemented between the two adjacent coils junction to avoid unwanted coupling between the two adjacent transformers. Simulations show that without the implementation of cross-connect wiring, the isolation between adjacent transformers degraded by 8 dB. All four coils are drawn symmetrically with respect to output port 5. One of the reasons to select parallel combining technique over series combing, is the equal distance between each transformer to the combining node. Hence all coils experience the same metal resistance and coupling characteristics from surroundings. While in series combing, as shown in Fig. 3 (b) one path exhibits lower resistive loss while the longer path experiences higher values of resistive loss, which results in uneven. Fig. 6 shows 3D view of a 4-to-1 combining network based on quarter wave length TL Wilkinson combiners. Metal m8 is used to design quarter wave length differential line. Width of the line is 6 um with spacing between the differential lines is 6 um to realize differential characteristic impedance of 70 Ohms. Top aluminum metal is used as ground between the adjacent inputs to improve the isolation.

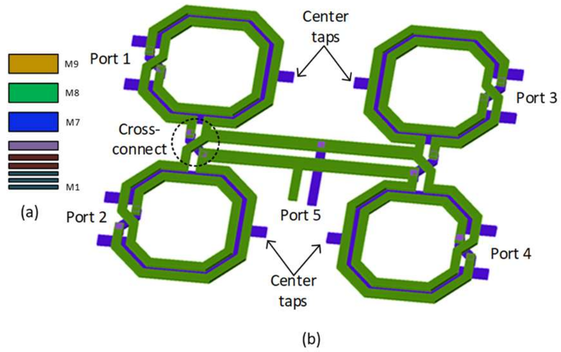

Fig 5: (a) Technology metal stack, (b) 3D diagram of transformer-based power combiner

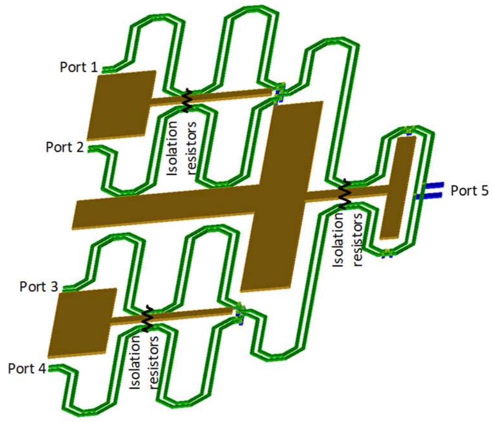

Fig 6: 3D view of Wilkinson combiners to design a 4-to-1 combining network

IV. RESULTS

Electromagnetic (EM) simulations are performed to optimize the designs. EM simulations are conducted using ADS Momentum 2.5 D tool from Keysight technologies. S-parameter results of transformer-based combiner are shown in Fig. 7 (a). Simulated loss is 1.5 dB to 3 dB in addition to fundamental loss of 6dB in port splitting, covering the frequencies from 23 GHz to 51 GHz. Isolation between the ports are at maximum -16 dB. Amplitude and phase difference between the ports is less than 0.2 dB and 0.3 degrees, respectively, as shown in Fig. 7 (b) and (c). Total area consumed is 330 um x 307 um. Fig. 8 shows insertion loss and isolation between two adjacent inputs of a 4-way Wilkinson power combiner network. An insertion loss of 3.7 dB to 6 dB is seen from 23 GHz to 40 GHz. Maximum isolation of -36 dB between the inputs is seen at 28 GHz with minimum isolation of -16 dB at other frequencies. Total area of Wilkinson combiner network is 1485 um x 700 um.

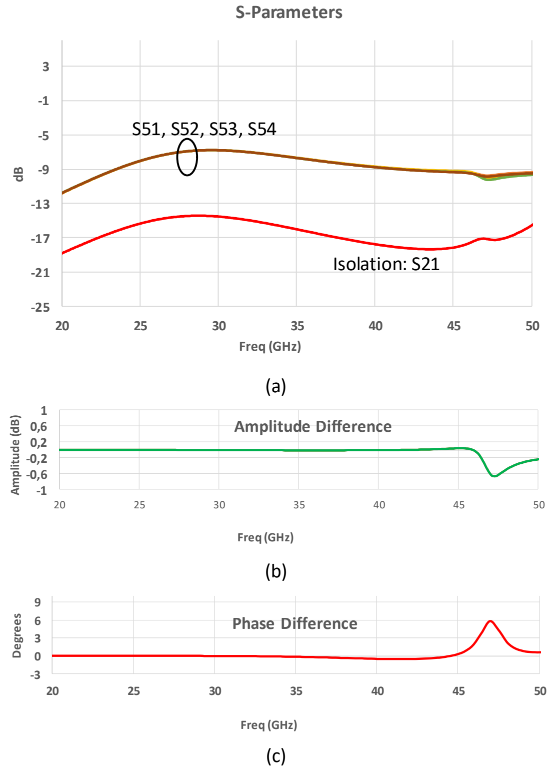

Fig 7: (a) Simulated S-parameters of transformer-based 4-to-1 power combiner, (b) amplitude difference between two differential ports, (c) phase difference between two differential ports

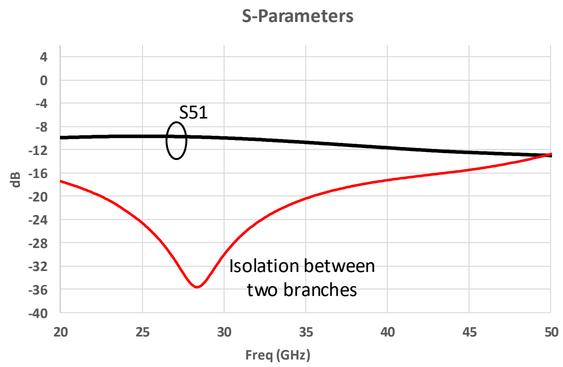

Fig 8: Simulated insertion loss and isolation of 4-way Wilkinson power combiner

V. Conclusions

In this work, some of the active and passive combining techniques for mm-wave frequencies are discussed, such as Wilkinson power combining, lumped element-based Wilkinson power combiner, current summing active combiner and transformer-based power combiner. Design of two 4–to-1 single-stage differential power combiners are presented from 23 GHz to 40 GHz, in 45 nm CMOS SOI technology. Transformer-based current combining technique is used to design a compact, fully differential power combiner. A 4-to-1 3 stage Wilkinson combiner is also presented for center frequency of 28 GHz. Simulation results show an insertion loss of 1.5 dB to 3 dB for transformer-based combiner while 3 to 6 dB for Wilkinson combiner. Total area of the transformer-based combiner and Wilkinson combiner is 0.101 mm^2 and 1.04 mm^2, respectively. From the results, it can be seen that compact size with sufficient isolation of transformer-based design makes it a suitable choice for combining or splitting array elements in a phased array for 5G systems.

TABLE I. Performance comparison

	Transformer based combiner	Wilkinson combiner
Freq (GHz)	23 - 40	23 - 45
Insertion loss (dB)	1.5 to 3	3.7 to 6
Isolation (dB)	14	36
Area (mm^2)	0.101	1.0395
Technology	45 nm CMOS SOI	45 nm CMOS SOI

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