28-31 GHz Bi-directional Amplifier for 5G Wireless Repeaters

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***Abstract*—A bi-directional amplifier circuit for fifth-generation (5G) communications systems is presented. The circuit uses two active quasi-circulators, one at the input and another at the output, plus two amplifiers. The amplifiers are identical in design, with one facing in the forward direction and the other the reverse direction. Simulated results show that the forward and reverse gain of the system are both close 20 dB between 28 GHz and 31 GHz. The output 1-dB compression point of the amplifier system is 0.3 dBm at the midband frequency of 29.5 GHz and the input 1-dB compression point is -20.3 dBm. The circuit was designed using Global Foundries' standard 130 nm CMOS technology.**

I. Introduction

The general vision for fifth-generation (5G) wireless networks is a multi-tiered heterogeneous network containing femtocells and picocells operating in the mm-wave band nestled within the existing network [1]. At millimeter wavelengths, wireless links are easily disrupted when the line-of-sight (LoS) between the transmitter and the receiver is broken. Thus, to extend a base station's coverage to 'dark' locations that are 'dark' in an office building or a city street, compact, low-cost two-way repeaters are needed. Long associated with long-distance microwave backhaul links, there is fresh new interest in the design of microwave repeaters/relay nodes but this time for indoor links [2], [3].

Either a reflection amplifier or a bi-directional amplifier can be used as the gain element in a repeater. This paper presents a bi-directional amplifier operating in the 28-31 GHz range—a candidate band for 5G networks. Among the bi-directional amplifier designs reported to date, some employ switches to separate the forward and backward traveling waves [4] while others rely on power couplers to do so [5]. Here, we explore a different concept that avoids switches and large passive power couplers and instead relies on active quasi-circulators and gain elements.

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II. Circuit Description

A. Bi-directional amplifier

A schematic diagram of the bi-directional amplifier is shown in Figure 1. As shown, the bi-directional amplifier consists two active quasi-circulators and two amplifiers. The active, transistor-based, quasi-circulator circuits are used at the input and the output of the bi-directional amplifier to separate the forward and reverse going waves. The amplifiers are used to amplify the output waves from the circulator and qualify the system specification.

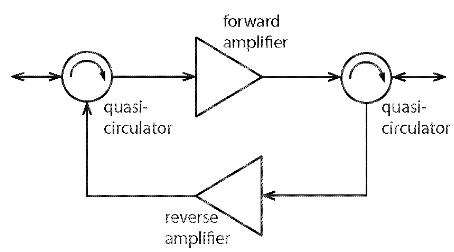

Figure 1. Schemetic diagram of the bi-directioanl amplifier

B. Active quasi-circulator

A schematic diagram of the active quasi-circulator is shown in the Figure 2. The circulator receives a differential input from port 1 while port 2 and port 3 are single-ended. When there is a signal incident at port 1, it goes through common-gate device M1 and exits at port 2 after passing through Gm1. When a signal is accepted at port 2, it goes through the top transconductance stage Gm2 and exits at port 3 [6].

Consider the port-to-port isolation. The incident RF signal at port 1 sees a symmetric circuit structure as it propagates through the circuit until it reaches the output node at port 3. Since the input in port 1 is differential, the signals that meet at port 3 cancel each other out. The shunt load impedance, Z0, located on the bottom branch, has the same value, 50Ohms, as the characteristic impedance seen at port 2 to preserve the symmetry. As mentioned above, an incident differential signal from port 1 goes through identical transconductance circuits to reach port 3. They cancelled each other due to 180° phase difference so that port 1 and port 3 are isolated.

A signal entering port 2 encounters high impedance at M1 because it enters the Gm1 in reverse from drain and as a result, port 2 and port 1 reverse isolation is provided. A signal entering port 3 meets the transconductance circuits Gm2 and Gm1 in reverse as well, so reverse isolation from port 3 to ports 1 and 2 is provided.

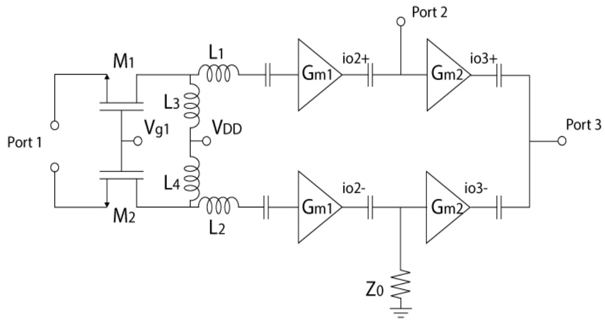

Figure 2. Schemetic diagram of Circulator

Amplifiers Gm1 are added after transistors M3 and M4 to amplify the RF signal and provide a higher output power before a RF signal exits the circuit via port 2. Figure 3 shows the schematic diagram of Gm1. The gain of amplifier is limited by transistor parasitic capacitance at high frequency. Therefore, the two-stage amplifier uses inductors to cancel the parasitic capacitance of the transistors and act as active load to maintain the same output level when frequency increases.

The transconductor block Gm2 used in the quasi-circulator to convert from voltage to current is shown in Figure 4. This circuit has two stages, a buffer stage and the transconductance stage.

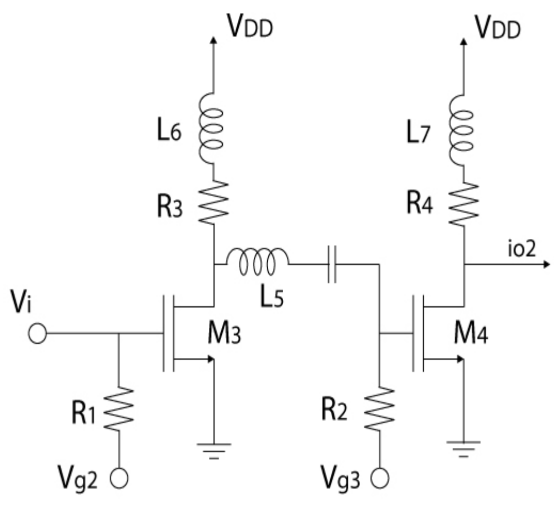

Figure 3. Schemetic diagram of Gm1 block.

The transconductance stage consists of two transistors. Transistor M7 is in a cascade arrangement relative to M6 and its purpose is to mitigate the Miller effect in device M6 and thereby extend its frequency response. The output signal current is taken at the drain of M7. Note that the inductance L8 is used as an active load. In princi ple, a cascade device can be used with PMOS transistors to make the circuit symmetric with the NMOS part. Nevertheless, that option was not pursued because the high operating frequency of this circuit works at, an inductor can act as load to reach higher output gain. With an inductor added at the top having three transistors stacked on top of each other, all biased from a single 1.2 V supply, the transistors would not have enough voltage headroom to achieve the required performance.

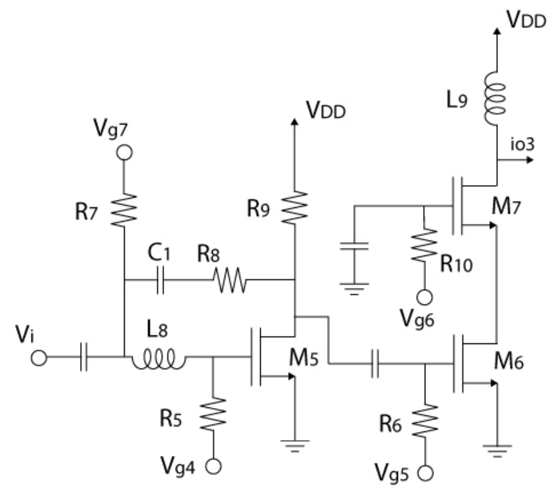

Figure 4. Schemetic diagram of Gm2 block.

The input impedance to the transconductance stage of Gm2 in Figure 3 is high, so a matching network must be added to avoid a high reflection coefficient at port 2. The solution chosen in this design was to insert a buffer stage with a moderately low input impedance ahead of the transconductance stage. The buffer is a simple common-source amplifier with resistive feedback. Although this solution added DC power consumption, it provides a low reflection coefficient over a wide bandwidth [6].

C. Amplifier

A schematic diagram of the amplifier is shown in Figure 5. The transconductance stage in the circulator itself cannot provide enough power gain for the output signal so a signal amplifier is added. A signal exiting from port 3 of the circulator goes into an amplifier stage, and enters the other circulator from port 1 [7][8].

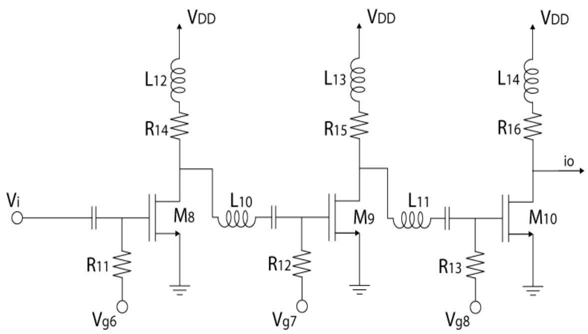

Figure 5. Schemetic diagram of forward and reverse amplifiers

A three-stage amplifier is designed to perform the forward and reverse RF signal amplify function. Different from the conventional three stage design, inductors are added between each stage to increase the output power at higher frequency by resonating with the parasitic capacitances which is the main limit of the gain of the amplifiers in high frequency applications. Each stage is tuned differently to magnify the gain of the amplifier and maintain the self-reflection coefficient at a reasonable low level. The inductor, transistor width and resistor measurements are shown in table below. All of the transistors are 130 nm in length.

TABLE I.

Inductor Values			
Component	**Value (nH)**	**Component**	**Value (nH)**
L1	1	L2	1
L3	1	L4	1
L5	0.5	L6	1
L7	1	L8	1
L9	1	L10	0.5
L11	0.7	L12	1
L13	0.9	L14	0.6
Transistor Dimensions			
Component	**Value (μm)**	**Component**	**Value (μm)**
M1	36	M2	36
M3	40	M4	40
M5	48	M6	40
M7	40	M8	30
M9	30	M10	36
Resistor Values			
Component	**Value (Ohm)**	**Component**	**Value (Ohm)**
R1	20k	R2	20k
R3	40	R4	40

Inductor Values			
Component	**Value (nH)**	**Component**	**Value (nH)**
R5	20k	R6	20k
R7	20k	R8	1k
R9	100	R10	20k
R11	20k	R12	20k
R13	20k	R14	80
R15	65	R16	40

III. Results

Considering half of the forward circuit, an active quasi-circulator plus an amplifier together, Figure 6 shows the forward transmit coefficient S21 and S32 are 10 dB and 15 dB at 31GHz.

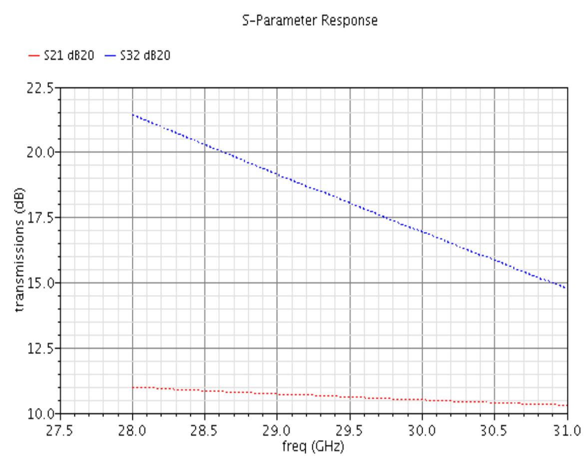

Figure 6. S-parameter S32 and S21 of forward circuit

Shown in the Figure 7, the self-reflection coefficient of the forward transmit circuit S11, S22, S33 are all below -10dB.

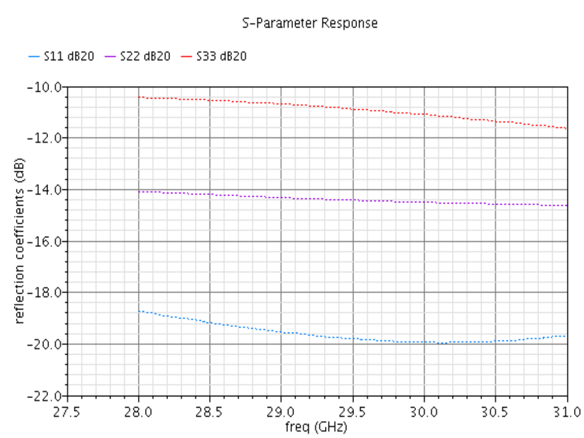

Figure 7. S-parameter of self-reflection coefficient

Considering the entire forward circuit. Signal accepted from port 2 of one circulator and exit from port 2 of the other circulator. Name the first port 2 as port 1 for argument.

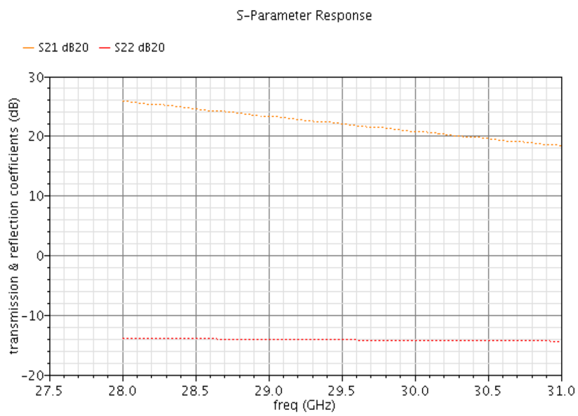

Figure 8. S-parameter S21 and S22 of bi-directional amplifier

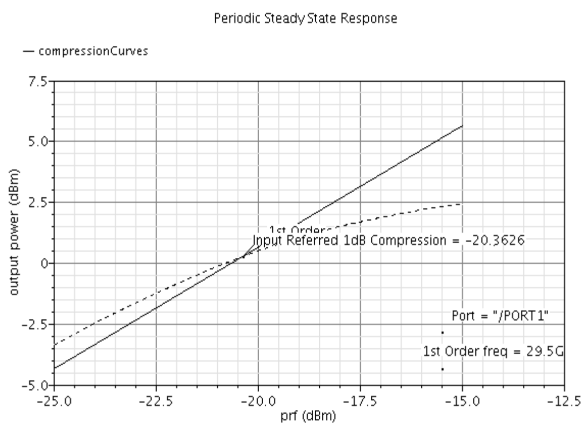

Figure 9. 1dB compression point of bi-directional amplifier

As shown in Figure 8, the self-reflection coefficient for the two ports of the bi-directional amplifier are -14 dB, and the forward transmit coefficient is above 18 dB through the 28GHz to 31GHz region.

The input 1dB compression point with a RF signal at frequency of 29.5GHz, shown in the Figure 9, is -20.3 dBm with the output power of 335 mdBm.

IV. Conclusion

In this paper, a bi-directional amplifier was designed and simulated. The design replaced switches and large passive power couplers with active quasi-circulators and amplifiers. The design features a forward transmission coefficient above 18 dB which offers good gain on the RF signal in the working frequency of 28GHz to 31GHz. It also has a good reflection coefficient below -14dB at two ports which provided a good impedance matching to the circuits connected. This design also has an output 1-dB compression point of 0.3 dBm and an input 1dB compression point at -20.3 dBm at the midband frequency of 29.5GHz. This design could be used as repeaters/relay nodes in 5G application at the frequency ranged from 28GHz to 31GHz.

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